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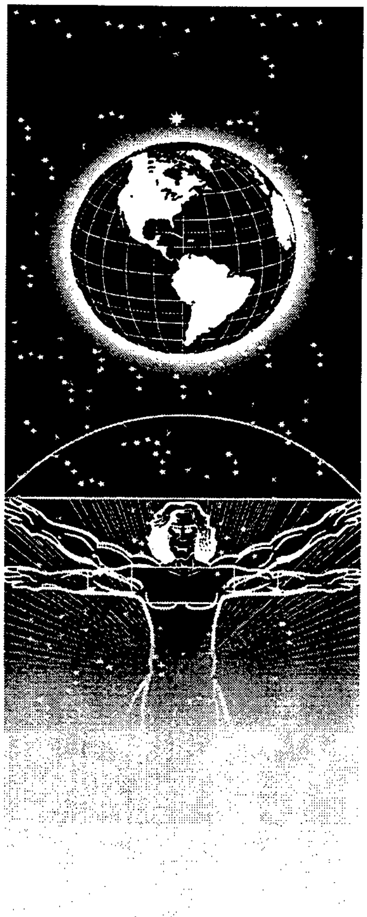

UNITED STATES AIR FORCE RESEARCH LABORATORY

A Survey of Immersive Technology For Maintenance Evaluations

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proved for public release; distribution is unlimited.

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FOR THE COMMANDER

, LtCol

FOR THOMAS J. MOORE, Chief
Crew Survivability and Logistics Division
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Virtual reality has come a long way since the turn of the decade and is continually growing, with extensive research by commercial, government, and educational agencies. This paper describes current virtual reality technologies available; undergoing virtual reality research & development; and issues related to those technologies that can be applied to simulated maintenance evaluations. There are still hardware and software issues that need to be overcome before virtual "presence" is truly felt. These issues include simulator sickness where the inner ear can not feel the translation motion unless it is physically experienced; and multi-person tasks where peripheral vision plays a major role in the accomplishment of the task and knowing the location of the other person

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PREFACE

This report documents the results of a study of the capability of virtual reality to supplement simulations in DEPTH which use a human figure model to visualize man-machine interaction and receive on-line human factors information simulations. This study was conducted as part of a logistics research and development program Design Evaluation for Personnel , Training, and Human Factors (contract number F33657-92-D-2055), managed by the Air Force Research Laboratory, Logistics Sustainment Branch (AFRL/HESS), Wright-Patterson AFB, OH. The primary focus of this program was to evaluate current and future virtual reality(VR) technology can be applied to simulated maintenance evaluations. Simulations, such as the ones DEPTH provides, aid in detecting maintenance problems early in weapon system acquisition

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1. INTRODUCTION

1.1 Objective

Computer-based human figure models (HFMs) provide a means of visualizing and evaluating maintenance activities for new system designs or modifications. HFMs were previously limited to static poses, but advances in computer technology now allow full motion for more informative human factors analyses. Armstrong Laboratory's Design Evaluation for Personnel, Training, and Human Factors (DEPTH) project is developing this technology for weapon system design analysis, technical manual generation, maintenance training, and logistics support analysis.

A user can create simulations in DEPTH using a HFM DEPTH to visualize man-machine interaction and receive on-line human factors information. Computer Aided Design (CAD) data can be used as a virtual mockup of the system design, minimizing the need for the costly physical prototypes. Due to this capability, design problems can be identified and fixed earlier in the process. In addition to design information, the simulations can provide important Logistic Support Analysis (LSA) information regarding safety, support equipment, hand tools, work force, and personnel. Text, graphics and animations can be captured for use in interactive electronic technical manuals (IETMs). Simulations, such as the ones DEPTH provides, aid in detecting maintenance problems early in weapon system acquisition.

AFRL/HESS is interested in assessing the capability of virtual reality to supplement these simulations. Based on studies conducted by AL/HRC, it was clear that immersing the user in the 3D world is an effective way to experience weapon system repair.

1.2 Approach

Battelle's approach was as follows::

1. **Conduct On-site Evaluations.** Conduct on-site evaluation of hardware resident in the Logistics Visualization Facility in building 434 and at other Wright-Patterson AFB organizations (e.g., AL/CFB's research in the Phantom device). This will also give more insight into the possibilities and limitations of immersion.

2. **Survey Literature.** In cooperation with AL/HRG, review technical reports, papers, and journal articles regarding immersive hardware and its application to design analysis. This area of research is evolving rapidly in the areas of operability, design and data visualization, and entertainment; therefore it will be necessary to keep a wide scope for the literature search.

3. **Survey On-going Work.** Accompany an AL/HRG representative to at least four locations (McDonnell-Douglas Aircraft Company, St. Louis; Boeing and the University of Washington, Seattle; and AL/HRT, Orlando) to assess real world applications of this technology.

2. DEFINITIONS

Ask three people what Virtual Reality is, and you'll probably get three different responses. Terminology for the world of virtual reality is changing constantly and the same terms mean different things to various people. Therefore, one of the first things needed in this report is a basic description of terms. The following terms are the major ones that need to be defined for a common basis of communication through the rest of the report. These definitions are from several Internet Web Pages which contain terms and definitions. Some of these individual items will have a numbered paragraph dedicated to their description and capabilities later in the report.

- **Augmented Reality** - The use of transparent head-mounted displays (HMDs) such as glasses on which data can be projected. This allows someone to repair a radar, for example, and have the needed data displayed on the glasses while walking around the radar. Precisely calibrated, rapid head tracking is required to sustain the illusion.
- **Haptic Interfaces** - Interfaces that use all the physical sensors that provide us with a sense of touch at the skin level and force feedback information from our muscles and joints. A haptic interface is a force-reflecting device which allows a user to touch, feel, manipulate, create, and/or alter simulated three-dimensional objects in a virtual environment. Such an interface could be used to teach physical skills for those jobs requiring specialized hand-held tools, to provide haptic feedback modeling of scientific concepts to trainees in a classroom, to enable modeling of three-dimensional objects without a physical medium, or to mock-up developmental prototypes directly from CAD databases.
- **Immersion** - The primary effect of immersion is to place a person into a simulated environment that looks, sounds, and feels to some degree like the real world. A person in this synthetic environment has a specific sense of self-location within it, can move their head and eyes to explore it, feel that the space surrounds them, and can interact with the objects in it. In immersive VR, simulated objects appear solid and have an egocentric location much like real objects in the real world. They can be picked up, examined from all sides, navigated around, heard, smelled, touched, hefted, and explored in many sensory ways.
- **Lag** - Delay between an action and its visual, acoustic, or other sensory feedback, often because of inherent delays in the tracking devices, or in the computation of the scene. This delay is one of the major causes of disorientation and simulator sickness.
- **Simulator Sickness** - The disturbances produced by simulators, ranging in degree from a feeling of unpleasantness, disorientation, and headaches to nausea and vomiting. Many factors may be involved, including sensory distortions such as abnormal movement of arms and heads because of the weight of equipment, long delays or lags in feedback, and missing visual cues from convergence and accommodation. Simulator sickness rarely occurs with displays of less than 60 degrees visual angle.
- **Virtual Reality** - A human-computer interface in which the computer creates a sensory-immersing environment that interactively responds to and is controlled by the behavior of the user.
  "The Silicon Mirage: The Art and Science of Virtual Reality" by Aukstakalnis & Blatner (1992) define Virtual Reality as "...a way for humans to visualize, manipulate and interact with computers and extremely complex data." Other terms that may be used for scientific purposes include: synthetic environments, immersive simulation, and virtual environments.

3. TECHNOLOGY SURVEYS

The technologies were surveyed by different methods: site visits, phone conversations, conferences, literature surveys, and Internet World Wide Web (WWW) searches. The initial group of scheduled site visits were determined by the SOW itself. From some of these visits, additional points of contact were discovered for other emerging technologies and these persons were visited. The following paragraphs gives a brief description of the technology and its current stage of development, the location of the development, and a point of contact. The Appendix describes in detail some of the hardware and software that was found that is applicable for use in an immersive environment.

3.1 Hardware

The first paragraphs will look at some of the different hardware that is being developed focus in the immersive environment. The hardware includes processors, input devices, output devices, and feedback devices.

3.1.1 Processors

There are two types of tasks in an immersive system: display and detection. For the immersive sense to be successful, the processor speed must be sufficiently fast enough that the computation speed for these two tasks is near real time. With advances in "chip" speed, basic processor instruction sets, and other computational advancements the problem changes from computational speed to input/output (I/O) bus speed.

3.1.1.1 Host Computers

The host computer serves to link all of the components in the virtual environment system together. It gives commands to the image generator, sound system, and force feedback system, and receives input from the trackers and data gloves. Since it doesn't take an incredible amount of computing power to perform these functions, a normal Pentium PC is powerful enough to serve as the host computer.

3.1.1.2 Image generators

An image generator is a digital electronic system for producing sequences of video images in real time. The IG uses a digital database of graphics objects to produce images that are sent to display devices. There are both low-cost and high-cost IGs, but for sophisticated applications, a high-cost IG is a must.

The image generator system is composed of the following components: an IG host, a geometry processor, a pixel processor, and a video processor. (The names of these components vary depending on brand name, but the functions remain the same.) The IG host is basically a computer that talks to the host computer. The IG host also performs database retrieval duties, as well as controlling special-purpose hardware. The geometry processor converts 3-D polygons into 2-D perspective polygons as seen from the current eyepoint. The pixel processor converts the polygons to pixels, and typically requires the most computing power, about 10 GFLOPS. The video processor converts the pixels to video, and sends the video to a display device.

Important performance categories for IGs include:

- Polygon capacity - The number of polygons that can be generated per second by the IG.
- Update rate - The frequency with which the IG calculates a new picture.
- Transportation delay - The lag time, or number of frames delay, of the IG when a new eyepoint position is received from the user interface. (Should be no longer than 2 frames.)

- Texture memory - The amount of texture memory on-line relates to the number of different texture maps which can be used to add variety to the scene.
- Anti-Aliasing - The ability to remove jagged edges on bitmapped displays by interpolating neutral colors or intermediate intensities.

Image Genorators (Igs) are still about 3 years away from being able to completely living up the expectations of the VE community. For every image generator, there is usually only one application to which the device is ideally suited.

3.1.2 Input devices

As stated previously, there are two types of tasks in an immersive system: display and detection. The next paragraphs will look at the detection part by taking a brief look at some input devices. Input devices provide different types of information to the host processor to determine current status and desired motion of the display. These devices determine current body location and position from trackers, and desired movement from joysticks and other input devices such as treadmills.

3.1.2.1 Body Trackers

Body trackers are used to track the motion of the user so that tasks can be performed in the virtual environment. There are a variety of tracker types: electromagnetic, optical, mechanical, acoustical, and inertial. There are advantages and disadvantages to each tracker.

Important performance characteristics for body trackers are:

- Tracking multiple points - Is the tracker capable of tracking more than one point?
- Accuracy and Range - Distance and how accurate are the trackers?
- Immunity to interference - What causes interference with the tracker?
- Lag - What kind of time delay is involved in using the tracker?

The general descriptions of the following tracking methods are from Jerry Isdale's "What Is Virtual Reality?: A Homebrew Introduction and Information Resource List ", Version 2.1, Oct 8 1993. (see URL: http://www.cms.dmu.ac.uk/~cph/VR/whatisvr.html).

Figure 1: Wireless Body Tracking System

3.1.2.1.1 Electromagnetic

Magnetic trackers use sets of coils that are pulsed to produce magnetic fields. The magnetic sensors determine the strength and angles of the fields. Limitations of these trackers are a high latency for the measurement and processing, range limitations, and interference from ferrous materials within the fields. However, magnetic trackers seem to be one of the preferred methods. The two primary companies selling magnetic trackers are Polhemus and Ascension. Figure-1 is a photograph of a "wireless" electromagnetic tracking capability that is now being marketed.

3.1.2.1.2 Optical

Optical position tracking systems have been developed. One method uses a ceiling grid of LEDs and a head mounted camera. The LEDs are pulsed in sequence and the camera's image is processed to detect the flashes. Two problems with this method are limited space (grid size) and lack of full motion (rotations). Another optical method uses a number of video cameras to capture simultaneous images that are correlated by high speed computers to track objects. Processing time (and the cost of fast computers) is a major limiting factor here. One company selling an optical tracker is Origin Instruments.

3.1.2.1.3 Mechanical

Mechanical armatures can be used to provide fast and very accurate tracking. Such armatures may look like a desk lamp (for basic position/orientation) or they may be highly complex exoskeletons (for more detailed positions). The drawbacks of mechanical sensors are the awkwardness of the device and its restricted on motion. Shooting Star Systems makes a low cost armature system for head tracking. Fake Space Labs and LEEP Systems make much more expensive and elaborate armature systems for use with their display systems.

3.1.2.1.4 Acoustical

Ultrasonic sensors can be used to track position and orientation. A set of emitters and receivers are used with a known relationship between them. The emitters are pulsed in sequence and the time lag to each receiver is measured. Triangulation gives the position. Drawbacks to ultrasonics are low resolution, long lag times and interference from echoes and other noises in the environment. Logitech and Transition State are two companies that provide ultrasonic tracking systems.

3.1.2.1.5 Inertial

Inertial trackers have been developed that are small and accurate enough for VR use. However, these devices generally only provide rotational measurements. They are also not accurate for slow position changes. They allow the user to move about in a comparatively large working volume because there is no hardware or cabling between a computer and the tracker. Inertial trackers apply the principle of conservation of angular momentum in miniature gyroscopes that can be attached to objects such as HMDs, but they tend to drift (up to 10 degrees per minute) and to be sensitive to vibration. Yaw, pitch, and roll are calculated by measuring the resistance of the gyroscope to a change in orientation.

3.1.2.2 Mouse devices

The following information was gathered from Gyration, Inc (Gyration, Feb. 1996-97).

In the 3D world of VR, it is not always intuitive how to interact with items like you do with a 2D mouse. To lessen this problem GYRATION, Inc., has the GyroPoint® Desk*, a next-generation pointing device. It combines standard on-the-desk mouse features with "in air", free-space movement to allow personal computer users to surf, scan and select software applications in a more intuitive and responsive way than using a traditional mouse.

GyroPoint Desk allows users to manipulate the computer cursor by picking up the lightweight device and then moving their wrist in the direction they would like to move the cursor: up, down, left, right or diagonally. Inside the product are two gyroscopes that sense the motion and move the cursor in the corresponding direction. The ergonomic GyroPoint Desk provides the freedom of movement - with a full 360 degrees of motion. The interactive pointer is plug-and-play compatible with Windows 3.X or later, Windows NT and Windows 95, and Apple Macintosh and PowerPC computers and all leading software applications.

The only current technology available to sense 360 degrees of movement is a gyroscope. Gyroscope technology is over 100 years old, but it wasn't until recently that the influence of modern technology was applied to the age-old sensor device. In 1991, GYRATION introduced the world's first digital miniature gyroscope based on optics designed for use by the commercial market. The gyroscope senses the up, down, left, and right movement of the hand and accurately manipulates the software on the computer or television screen. For decades, the sensing ability of the gyroscope has kept airplanes level and ships on course. GYRATION has a U.S. patent on its digital-based gyroscope technology.

GYRATION, Inc. designed the world's first miniature optical spin gyroscope, resulting in technology and usage patents in the U.S. The company's mission is to provide gyroscope technology to a wide range of industries and applications with emphasis on the multimedia and interactive television markets. Its first commercial product, GyroPoint, a pointing device designed for presenters, was introduced in 1991. Established in June 1989, GYRATION has 50 employees and is privately held. The company is based in Saratoga, California.

3.1.2.3 Joysticks

For use in a 3-D virtual environment, a standard joystick with attached base might be difficult to use for navigation and item selection. As a result, there are baseless joysticks available for the virtual traveler. Figure 3 is a commercial example of this hardware that is made by General Reality Company (CyberStick).

Figure 2: Baseless 3-D Joystick Example

3.1.2.4 Gloves and Body Suits

The following general information on gloves and body suits derived from *Virtual Reality The Technology And Its Applications* (Monnet, 1995).

The data glove is put on the hand, and can then be "seen" as a floating hand in the Virtual Space. Input gloves generate finger-bend data allowing hand gestures with the pitch and roll of the hand. It can be used to initiate commands. For example, in Virtual Spaces where gravity does not exist, pointing the glove upwards could make the person appear to fly. Pointing downwards would then take him or her safely back to the ground. In this regard, the virtual hand is like a cursor on a standard PC, able to execute commands by pointing at a particular icon and 'clicking'.

Some gloves rely on optical fibers to convert the hand movements into signals to the computer. One problem with the glove is the need to provide a sense of touch to increase the haptic experience of the wearer. Consider what happens when a human reaches out to grip a virtual object. Although the virtual image shows he or she is gripping an object, the human cannot feel any resistance to the hand tightening movement. Work is under way to achieve this illusion by making the glove resist further closure. The gloves are not without their difficulties. They can be tiring and feel artificial. Indeed, some commentators question the future of the data glove as an input device, though there seems little alternative for sensory output to the hand. Frequently, users of VR are encased in an entire lightweight body suit. This suit has fiber optic cables or motion sensors at the major joints allowing the VR computers to track the user's movements precisely.

In time, the density of sensors which can be placed about the body will increase, enabling more accurate portrayals of movement. As with other input devices, enhancements will be made to incorporate output as well. As haptic displays which transmit the sense of touch and force feedback become more prevalent, other physical stimuli can be applied by such a suit.

3.1.2.5 Treadmills

One of the most difficult problems facing the integrators in a virtual environment is the realistic locomotion within the environment. Use of a wand, mouse, or some other nonrealistic input device removes some of the true sense of immersion, if only momentarily. The advent of the Omni-Directional Treadmill (ODT) lessens, if not eliminates, this problem. Virtual Space Devices, Inc., (VSD) with the support of US Army STRICOM, has designed, developed, and shipped the first ODT. An individual walking or running on the surface of the ODT within a computer-generated environment can navigate in any direction, and the device maintains the user's position at the device center. An ODT/VR system permits an immersant to navigate naturally within a synthetic environment, employing off-the-shelf solutions for scenegraph generation, display, sound, and whole body tracking. Combination of separate ODT systems would permit sharing of a common synthetic environment by large numbers of individual participants.

Some of the basic technical details include:

- Surface moves in any direction, allowing user to walk in a circle.
- Active surface is 1.3 x 1.3 meters [50" x 50"] with velocity to 3m/sec [6 mph].
- ODT is basically composed of two belts, one for X direction, one for Y direction. The X belt is supported by the Y belt, and is mechanically transparent so that Y motion is conducted up through the X belt to the surface. Mechanical transparency permits both X and Y components to be present at the same time.
- Each belt is made from approximately 3400 separate rollers, woven together into a mechanical fabric.
- Each belt is controlled by its own servo motor.

Additional initial information can be found on the WWW at URL: http://www.vsdevices.com/.

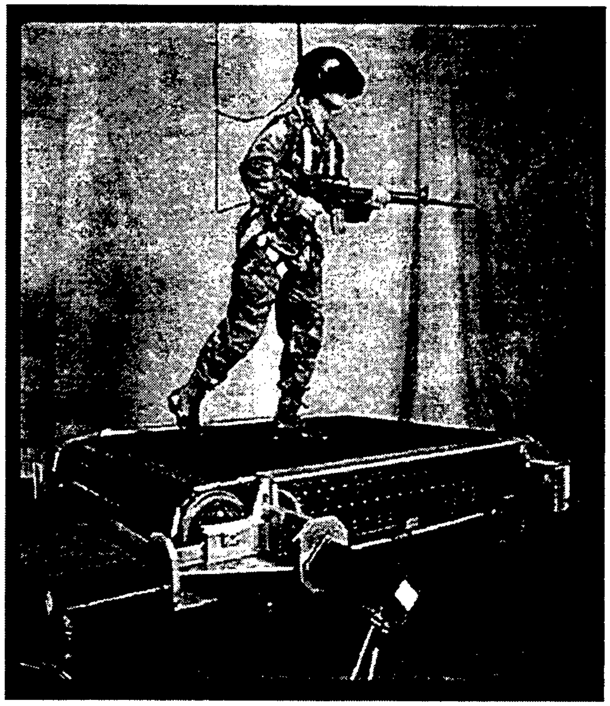

Figure 3: Omni-Directional Treadmill

3.1.3 Output Devices

The other part of the equation for providing a good immersive environment is the output from the processors. This is what provides the "feel" of immersion to the user through the visual and auditory cues that are provided.

3.1.3.1 Optical Displays

One of the most significant hardware requirements for an effective immersive environment will be the displaying of the environment. Currently there are various types of displays that would be appropriate depending on the application environment. There was a panel discussion at the SIGGRAPH '96 Conference titled "The Future of Virtual Reality: Head Mounted Displays Versus Spatially Immersive Displays" (Lantz, 1996). Mr. Ed Lantz of Spitz, Inc. described the spatially immersive display (SID) as a walk-in display which "physically surrounds the viewer with a panorama of imagery, typically produced by video projection." Mr. Lantz offered the following opinion at the beginning of the discussion:

> "...SIDs offer advantages over HMDs, including group viewing and interaction, wide field of view, high resolution, no cumbersome headgear, and low user fatigue. Also, angular viewing is accomplished without

head rotation tracking and its associated response time requirements. Stereoscopic displays are also possible using eye-sequential glasses.
A number of technical challenges remain in the development of both HMDs and SIDs. Currently VR researchers are consumed with refining the HMD. Advances are being made in wide field-of-view, high resolution HMD technology. Very little research is currently underway on SID implementation..."

The consensus of the panel discussion that followed the opening comments was that the display method should be determined by the application/task for which it is used. For larger collaborative groups, a virtual display table, projection screen, or monitors with 3-D glasses might be best. For an individual task assessment in a virtual environment, HMDs or virtual retinal displays (VRDs) would be more applicable. Some key points were voiced by panel member Bertrand de La Chappelle of VIRTOOLS on the need for the advancement of SID technology:

...HMDs are globally ill-adapted for day-to-day professional applications. A key founding component of the VR concept, HMDs have surely become less cumbersome, less expensive and have increased performance. But:

- Even if high resolutions and wide field of view (required for professional applications) ultimately appear, price/performance ratio is mostly driven by games; therefore, price will decrease faster than performance improves.
- Weight, eye, and neck fatigue prevent use over several hours; this is not likely to change even with greatly improved performances.
- Psychological factors are an important limitation: engineers and decision-makers are very reluctant to use such apparatus, considered game gear.
- HMDs isolate users from one another; collaborative work in the same room requires the creation of sophisticated clones, and people can bump into one another.

The main obstacle for HMDs will not be performance, but seclusion. Therefore, they will prosper in applications where people work in isolation for short periods of time and really need to look around them as if they were in a static real environment. Apart from games, the best applications include training and some maintenance assessment. In most other individual uses, devices like the BOOM™ or the Push™ from Fakespace seem more appropriate, offering high resolution, wide field of view, and less fatigue.

SIDs offer the best potential for collaborative applications. They still suffer major drawbacks: underdeveloped, very expensive, requiring much more space and hardware (three channels for the CAVE), they are not yet fully industrialized or standardized. But:

- They provide a better sense of presence through a very large field of view (up to 180x for the ARC Dome) and a high resolution (2000 x 2000 and up).
- They allow prolonged work through reduced fatigue, including in stereoscopy.
- They allow the presence of multiple users in the same environment, who can communicate naturally together.
- Large models can be displayed (cars, plane segments, plant sections) at once, whereas you need to turn your head around with an HMD.
- They are very well adapted for applications in which the user interacts strongly with the environment through Virtual Tools (3D widgets) and a 3D interface.

As VR applications evolve from simple walkthroughs towards virtual working environments, SIDs might become the new paradigm for professional use. Key developments in graphics hardware (new generation SGIs) and projection devices (mono-lens high power light valve or future micromirrors) will create a range of standard systems, from individual large screen displays to full-fledged multi-participant domed environments. Present prices will go down, thanks to entertain-ment applications (including immersive prerecorded rides), and such environments are the key to implementation of full concurrent engineering in manufacturing.

The following paragraphs describe some of the SIDs and HMDs that have been alluded to in the foregoing paragraphs.

3.1.3.1.1 Virtual Workbench Projected Image Display System

According to Fakespace's Internet web site at URL: http://www.fakespace.com/new_pro.html:

> "At SIGGRAPH '96, Silicon Graphics, Inc. and Fakespace debuted the Immersive Workbench projected image display system. Based on original work performed at the German National Computer Science and Mathematics Research Institute (GMD), and further developments by Stanford University, the Fakespace Immersive Workbench is a promising new working environment for scientific visualization and virtual reality applications.
>
> With an adjustable viewing surface -- from horizontal toward vertical -- the Immersive Workbench accommodates a wide range of work styles for varied applications, including scale model manipulation in design projects, medical visualization, and displays of complex three-dimensional data sets. The open table design supports collaborative workgroups and easy access to any segment of a computer model.
>
> The Immersive Workbench is available in several configurations. Early adopting Fakespace clients like Silicon Graphics, NASA Ames Research Center, and Naval Research Labs are providing input on future design enhancements. Figure 5: Virtual Workbench shows a form of the workbench. " Table 1: Virtual Workbench Technical Specifications gives the specifications.

Figure 4: Virtual Workbench

Table 1: Virtual Workbench Technical Specifications

System Requirements	Driven by SGI or equivalent graphics engine. Requires RGB sequential video up to 1600 x 1200 @ 60 Hz (monoscopic) and 1280 x 1024 @ 120 Hz (stereoscopic)
Viewing Table Dimensions	36"H x 100"W x 75"D
Table Positions	Adjustable from Horizontal toward Vertical
Complete System Footprint	36"H x 100"W x 144"D
Power	120V AC, approximately 7 Amps
Interaction	PINCH glove included in system, other 3D pointing devices optional
Display:	Electrohome Marquee 9500 Series, other projector displays optional. StereoGraphics Crystal Eyes included, other shutter glasses optional
Tracking:	Choice of Ascension, Polhemus, or Logitech included, other tracker systems optional

The Interactive Workbench is used by the Numerical Aerospace Simulation (NAS) facility at NASA Ames Research Center (ARC) to visualize the massive amounts of information for its "Virtual Wind Tunnel" software which is run on a Silicon Graphics machine (NASA Ames Research Center, 1997). The workbench is horizontal rear-projection screen interface used to display a massive amount of and complex information to large groups of people. The output device is part of the Ames NAS Large Scale Interactive Visualization Environment (LIVE). LIVE is a resource for visualization and analysis of large-scale datasets at the NAS Facility at ARC. LIVE is a system with dedicated CPU, memory, disk, software, and consulting support to aid users in the analysis of large or complex datasets. Large amounts of disk storage allow users to store their very large datasets. Multiple CPUs and gigabytes of memory allow for interactive access to large amounts of data at one time. This provides an environment where a user can get most or all of the data in one place for analysis.

3.1.3.1.2 CAVE™

The following description was found in the Pyramid Systems, Inc. WWW information page at URL: http://www2.pyramidsystems.com/psi/CAVE.html.

In addition to the well-known mode of virtual reality visualization hardware, head-mounted displays, the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago has within the last few years introduced a third mode: a room constructed from large screens on which the graphics are projected on three walls and the floor.

The CAVE™ is a multi-person, room-sized, high-resolution, 3D video and audio environment. Graphics are rear projected in stereo onto three walls and the floor, and viewed with stereo glasses. As a viewer wearing a location sensor moves within its display boundaries, the correct perspective and stereo projections of the environment are updated, and the image moves with and surrounds the viewer. The other viewers in the CAVE are like passengers in a bus, along for the ride!

"CAVE," the name selected for the virtual reality theater, is both a recursive acronym (Cave Automatic Virtual Environment) and a reference to "The Simile of the Cave" found in Plato's "Republic," in which the philosopher explores the ideas of perception, reality, and illusion. Plato used the analogy of a person facing the back of a cave alive with shadows that are his/her only basis for ideas of what are real objects.

The CAVE premiered at the ACM SIGGRAPH 92 conference. It is achieving national recognition as an excellent virtual reality prototype and a compelling display environment for computational science and engineering data.

Rather than having evolved from video games or flight simulation, the CAVE has its motivation rooted in scientific visualization and the SIGGRAPH 92 Showcase effort. The Showcase event was an experiment; the Showcase chair, James E. George, and the Showcase committee advocated an environment for computational scientists to interactively present their research at a major professional conference in a one-to-many format on high-end workstations attached to large projections screens. The CAVE was developed as a "virtual reality theater" with scientific content and projection that met the criteria of Showcase. The Showcase jury selected participants based on the content of their research and its suitability to projected presentation. Figure 6: Artist Rendering of the CAVE is an illustration of the CAVE display system.

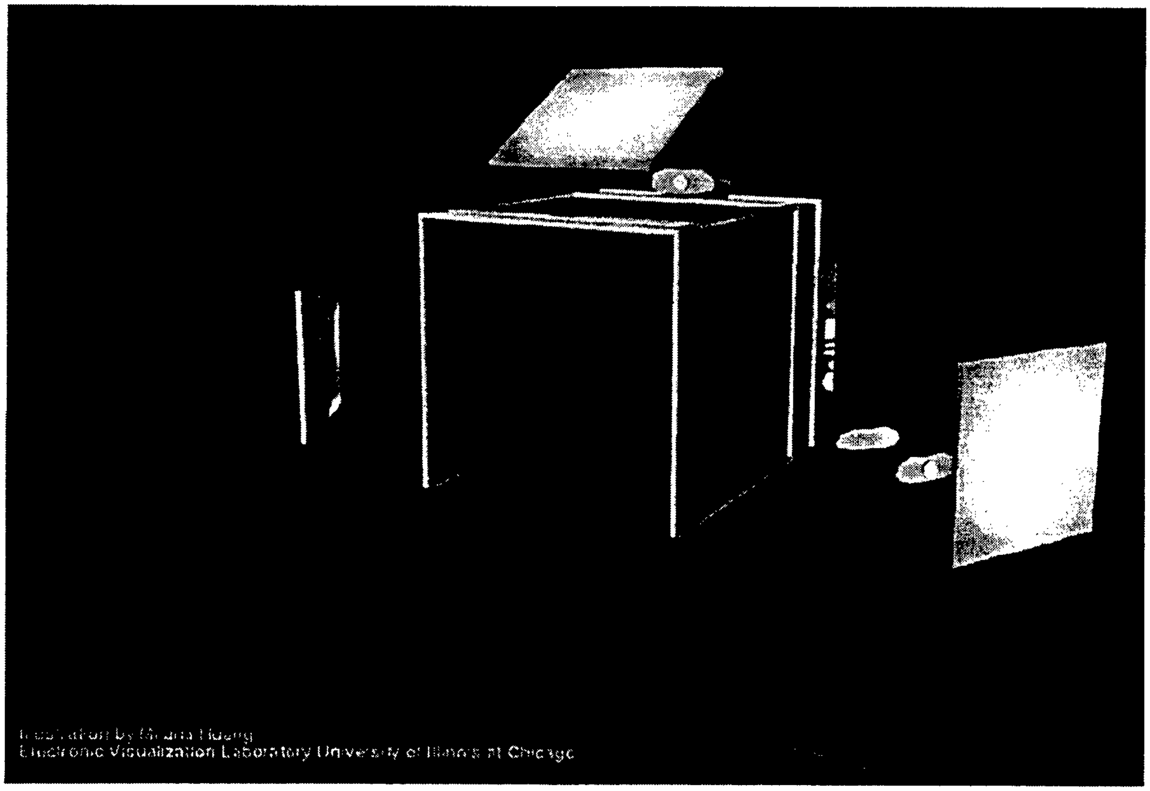

Figure 5: Artist Rendering of the CAVE

The challenge was attracting leading-edge computational scientists to use virtual reality. It had to help them get to scientific discoveries faster, without compromising the color, resolution, and flicker-free qualities they have come to expect using workstations. Scientists have been doing single-screen stereo graphics for more that 25 years; any virtual reality system had to successfully compete. Most important, the virtual reality display had to couple remote data sources, supercomputers, and scientific instrumentation in a functional way. In total, the virtual reality system had to offer a significant advantage to offset its packaging. The CAVE, which basically met all these criteria, had success in attracting serious collaborators in the HPCC community.

To retain computational scientists as users, there has been an attempt to match the virtual reality display to researchers' needs. Minimizing attachments and encumbrances have been goals, as has diminishing the effects of errors in the tracking and updating of data. One overall motivation is to create a virtual reality display that is good enough to get scientists to get up from their chairs, out of their offices, over to another building, perhaps even to travel to another institution.

The CAVE is a theater 10ftx10ftx9ft, made up of three rear-projection screens for walls and a down projection screen for the floor. Electrohome Marquee 8000 projectors throw full-color workstation fields (1024x768 stereo resolution) at 96Hz onto the screens, giving 2,000 x 2,000 linear pixel resolution to the surrounding composite image. Computer-controlled audio provides a sonification capability to multiple speakers. A user's head and hand are tracked with Polhemus or Ascension tethered electromagnetic sensors. Stereographics' LCD stereo shutter glasses are used to separate the alternate fields going to the eyes. A Silicon Graphics' Onyx workstation with three Reality Engines is used to create the imagery that is projected onto three of the four walls. (Prior to the Onyx, we used four Silicon Graphics Crimson Reality Engine workstations to create the imagery for four walls, plus a Silicon Graphics Personal IRIS that served as a master controller for the system. All workstations then communicated via a ScramNet optical fiber network from Systran Corporation.) The CAVE's theater area sits in a 30ftx20ftx13ft light-tight room, provided that the projectors' optics are folded by mirrors.

Goals that inspired the CAVE engineering effort include:

- The desire for higher-resolution color images and good surround vision without geometric distortion
- Less sensitivity to head-rotation induced errors
- The ability to mix virtual reality imagery with real devices (like one's hand)
- The need to guide and teach others in a reasonable way in artificial worlds
- The desire to couple to networked supercomputers and data sources for successive refinement

Over the past years, as the CAVE was being built, there were several inherent problems with head-mounted virtual reality technology to which a great deal of thought has been given:

- Simplistic real-time walk-around imagery
- Unacceptable resolution (the popular head-mounted displays offer resolution that is twice as bad as being legally blind)
- Difficulty of sharing experiences between two or more people
- Primitive color and lighting models
- No capability for successive refinement of images
- Too sensitive to rapid head movement
- No easy integration with real control devices
- Disorientation a common problem
- Poor multi-sensory integration, including sound and touch

The CAVE provides these current capabilities and engineering results:

- A viewer is presented with dynamically moving full-color images at 2,000 x 2,000 pixel resolution in stereo on the walls and floor. The images truly float in space allowing the viewer to walk around them.
- The primary viewer's position is tracked so that the correct perspective views are generated in real time. Head rotation is used to subtly adjust the perspective, not swing the entire world as in head mounted displays.
- The primary viewer can navigate with a variety of intuitive navigational devices currently under test and construction. At interesting points, the viewer can freeze the viewpoint and automatically provide the computer-graphics system with enough time to fully render the image (called "successive refinement"). The viewer may still rotate his/her head to take in the entire refined scene and still achieve a good stereo effect without requiring recomputation. Interestingly enough, the image still tracks you somewhat, akin to how the full moon seems to follow you as you walk, an effect that is quite striking.
- All viewers wearing LCD shutter glasses can see full 3D stereo projected into the room. In 3D movies or workstation stereo, objects must be kept near the center of the screen or behind the screen because the edges of the display cause the illusion to be destroyed for objects between the viewer and the screen (this is called "edge violation"). The CAVE edges are easy to keep out of view due to its wrap-around screens; projection into the room is not only possible but the best part.
- Since all viewers can still see their hands, body, and feet, they do not need training to stay oriented in the virtual space. Disorientation common in head-mounted displays is not an issue with the CAVE, unless specifically

induced. The 10'x10' CAVE allows groups of people, up to 12, to be led by a scientist/demonstrator to interesting places, a preservation of the teacher/student relationship not possible with head-mounted displays.

- A MIDI synthesizer is connected via Ethernet/PC so, for example, sounds may be generated to alert the user or convey information in the frequency domain.
- A second tracker is currently implemented on a 3D wand with buttons. There are analog-to digital boards to interface to other physical input devices.

Applications run in one of two modes: locally on the Onyx/CAVE and/or distributed between a backend computer and the Onyx/CAVE. In distributed computing mode, CAVE participants may "interactively steer" simulation codes. In local mode, CAVE participants either steer modest simulations or explore precomputed datasets.

Scientific simulation codes are typically large and complex. They require DPCC resources - scaleable computers, vector processors, massive datastores, large memories, or high-speed networks- to run efficiently. Depending on the dataset and type of analysis scientists want to do, they set up their simulation codes to calculate greater detail, a different time step, or a different state defined by new parameters. In distributed mode, CAVE users explore and experience visualizations of datasets, identify an area they want to enhance, and then invoke simulation codes on the networked computers to compute new datasets. The backend machine generates new data, which is then transferred to the Onyx for rendering and display in the CAVE.

To date, the CAVE has been networked to several backend machines: Thinking Machine Corporation's CM-5, a Silicon Graphics Challenge Array, and an IBM SP-1 and SP-2.

Table 2: The Cave Technical Specifications

Tracker	6 DOF
Display resolution	2500 x 2000 addressibility per screen
Horizontal scanning frequency	15-130 kHz
Vertical scanning frequency	38-180Hz
Bandwidth	125 MHz
Dimensions	Operating position 104"H x 73.5" W x 84" D;
Storage/Transport position	82" H x 73.5" H x 34"

3.1.3.1.3 Stereoscopic Display Glasses

The following general description is an excerpt from a paper presented at Stereoscopic Displays and Applications VII at San Jose, California in February 1996 by Woods, Docherty, and Koch. Although the paper is titled "3D Video Standards Conversion", it outlines some of the various methods used to produce stereoscopic vision encoding and decoding.

> The more common method used is field-sequential encoding. In this system, video fields are alternately encoded with right or left information. The popularity of this system is a result of its simplicity. Field-sequential 3D Video is easily generated from a pair of genlocked video cameras by using a video multiplexer which selects odd fields from the right camera and even fields from the left camera. The 3D video signal can be recorded and played back with standard video cassette recorders (VCRs) and it can be viewed in 3D quite simply using a standard television, a pair of liquid crystal shutter glasses and a small device which synchronizes the glasses with the left and right images being displayed on the screen.
>
> Field-sequential 3D video does have a problem with flicker when used with a standard television because each eye only receives half the overall field rate (25Hz for PAL and 30Hz for NTSC). The flicker problem can be overcome by using commercially available field doublers.
>
> With field-sequential 3D video there are two polarities by which left and right images can be stored in the odd and even fields. Most companies have chosen to store right images in the odd fields and left images in

the even fields (3DTV Corporation, VRex Inc, Virtual I/O, SOCS Research, etc). Some systems, however, use the opposite polarity, e.g. the Toshiba 3D camcorder. The result of this is that 3D video generated with one system cannot be viewed correctly on a system with the opposite polarity. The incorrect image will be sent to each eye and a pseudoscopic (reversed stereo) image will be seen by the viewer and incorrect DEPTH information will be perceived. Some systems are, however, compatible with both polarities by changing an external switch.

Figure 7: Example of Stereographic Glasses is an example of the stereographic glasses that are worn and the synchronization box for viewing the images.

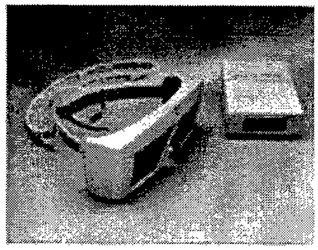

Figure 6: Example of Stereographic Glasses

3.1.3.1.4 Head Mounted Displays

Head Mounted Displays (HMDs) project the images of the virtual environments directly in front of the eyes. HMDs can display 3-D images with the use of stereographic viewing. There are a variety of display types that include CRTs, LCDs, and Fiberoptics.

Important performance characteristics for HMDs are:

- Field of View - how much of a scene can be observed in the HMD at one time. (A horizontal field of view of 80 to 100 degrees is often cited as the threshold of immersion.)
- Resolution - the clarity of the picture seen in the HMD.
- Lag - the lag time associated with the HMD. The lag should be 75 milliseconds or less.
- Update rate - the number of pictures run per interval of time. The update rate should be targeted at around 60 Hertz.
- Weight - the actual weight of the HMD.

Figure 8: Examples of (a) Past and (b) Current Generation HMDs show a first generation and current generation example of HMDs. The following information on the DoD's initiative to improve HMD images can be found at URL: http://eto.sysplan.com/ETO/Displays/HMD/index.html as of November 1996.

The Defense Advanced Research Projects Agency (DARPA) established its Head Mounted Displays (HMD) program in 1992. DARPA initiated the program with the goal of creating small, flat-panel, high-resolution displays that can be mounted in novel ways to replace heavy, expensive, and bulky cathode ray tubes and offer new methods of presenting visual information to individuals on the battlefield. The HMD systems and miniature display technologies developed under this program will provide US military forces with discriminating information technology advantage and US manufacturers with a technological leading edge in a globally competitive market.

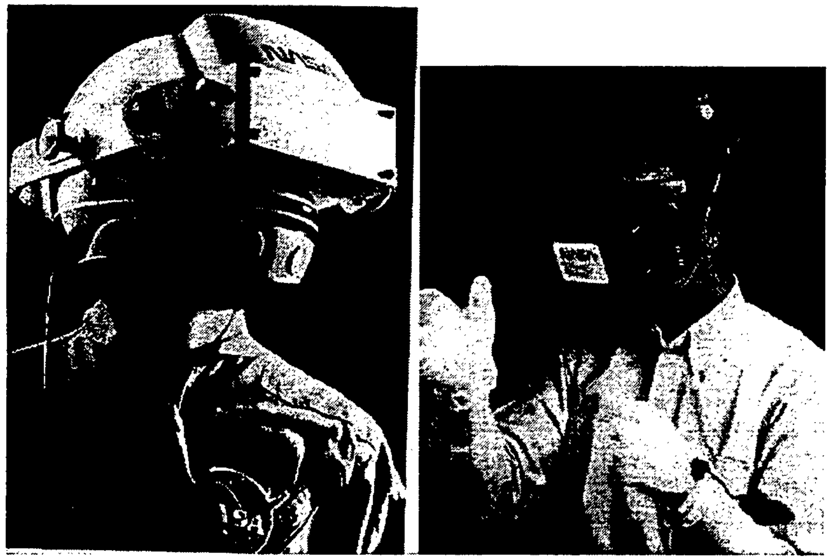

Figure 7: Examples of (a) Past and (b) Current Generation HMDs

The emphasis of the HMD program is on providing information to people where ordinary direct view display are either inappropriate or impractical. HMDs have unique applications in virtual environments where total immersion is important, in environments where hands-free operation is desirable or necessary, and in applications involving unique viewing requirements, such as 3-D, mapping graphical images onto real images, night vision, etc. As high-resolution, small format displays become available at affordable prices, it is expected that they will find applications in a variety of personal and portable systems. A goal of the HMD program is to develop eyeglass-like displays that can be coupled with computational, storage, and wireless devices to make a portable commercial and military information system for a wide variety of applications.

The program has already claimed significant achievements in high-resolution microdisplays including: the world's first 1000 dots-per-inch (DPI) active-matrix liquid crystal display (AMLCD) and active-matrix electroluminescent (AMEL) display fabricated on single crystal silicon; 512 x 512 reflective ferroelectric LCD (FLCD) fabricated with standard CMOS technology using color sequential lighting; and a unique 640 x 480 pixel, color, refractive LCD display on 5 mm2 also based on conventionally fabricated CMOS circuits with pixel layouts that can be arranged in a pre-distorted pattern to compensate for optical distortions.

A variety of supporting technologies have also been funded, including backlights, color filters, polarizers, low voltage electroluminescent materials, and optics. Supporting technologies can boast significant achievements: a low-cost, backlight efficiency enhancement, which, when combined with a reflective backlight chamber, increases the efficiency of LCD backlights by 45%; new high-brightness, high-efficiency, and sequential color backlights; and finally a low-voltage AMEL technology which will significantly reduce power and electronics requirements for AMEL displays.

HMDs developed under this program have already begun to migrate into military systems. The US Army's first HMD for a mounted soldier was developed under this program. The Combat Vehicle Crew (CVC) goggle incorporates the 1280 x 1024 AMEL display into a standard Army sun, wind, and dust goggle with a unique, lightweight optics design so that the entire system weighs only 11 oz. The first CVC goggle application will be for an M1A2 tank commander. Follow-on applications within the USA are planned to include the Land Warrior and Force XXI Soldier and with a slight variation of the goggle will be demonstrated in the Commanche helicopter. The Army's Advanced Visionics System is using DARPA developed displays to achieve full color, 1280x1024 pixel formats for helicopter pilots. The first Full Immersion HMD was demonstrated for use in a military cockpit simulator. A head-worn augmented reality system is being developed for use in military and commercial aircraft assembly and maintenance. The system utilizes a high-resolution HMD with highly refined optics and head trackers to accurately overlay design drawings and engineering information on the employee's workspace. This system will have applications in all military engineering and assembly environments that have converted to CAD/CAM systems. In addition numerous belt-worn maintenance HMD systems which contains engineering design and maintenance information formatted for field maintenance personnel have been developed using VGA microdisplays developed under this program.

The current program is supporting the continued development of both AMLCD and AMEL displays. Both technologies have a goal of making 2000 DPI displays. Applying color filters to these displays will provide a 1280 x 1024 color displays in one square inch. An Advanced Flat Panel HMD will be developed which will integrate these high-resolution color displays into HMDs for military medical applications. Development will continue on an extremely low-voltage AMEL technology. The goal is to bring the voltage down to standard CMOS levels. This will further reduce power and electronics requirements making AMEL displays an optimum solution for portable military HMD systems.

Future challenges for the HMD programs will be to continue to push the envelope in performance and lower power for miniature display technologies for high-information-content capability in a wearable system. At the same time, the program will focus on HMD systems issues critical to successful applications including: novel optics approaches for wide field-of-view displays in small, lightweight, form factors; reductions in display power consumption and electronics complexity; adapting new human interface techniques to the HMD information system; and developing scaleable tools, such as compression techniques and image processors for matching information with the display, and performing extreme integration of components and electronics. HMDs will be the most critical performance factor for the individual soldier of the future. DARPA will be working over the next several years to assure that the soldier is not performance-limited, but has greatly enhanced performance to meet the demanding information needs of the future battlefield.

3.1.3.1.5 VRD

The Virtual Retinal Display (VRD) team has been focused on developing improvements to the current prototype systems and on creating the parts needed for future prototypes. The VRD, based on the concept of scanning an image directly on the retina of the viewer's eye, is being developed at the University of Washington's HITL under a four-year program funded by Microvision, Inc. The program began in November 1993 with the goal of producing a full color, wide field-of-view, high resolution, high brightness, low cost stereo display in a package the size of conventional eyeglasses.

Two prototype systems are currently being demonstrated. The first is a bench mounted unit that will display a full color, VGA (640 by 480) resolution image updated at 60 Hertz. It will operate in either an inclusive or see-through mode. The second is a portable unit that will display a monochrome, VGA resolution image. The portable system is housed in a briefcase allowing for system demonstrations at remote locations.

Techniques that expand the system's exit pupil, making it easier to align one's eye to the display, have been developed and demonstrated for a monochrome display. Work is continuing to optimize the design and to develop components that will expand the pupil of the color system.

The largest component in the portable system is the commercially purchased vertical (60 Hertz) scanner. A new vertical scanner is being designed that should significantly decrease devices size and cost. Once this design is complete a head-mounted demonstration prototype will be assembled. Figure 9: Virtual Retinal Display Prototypeis a photograph of one of the recent prototypes.

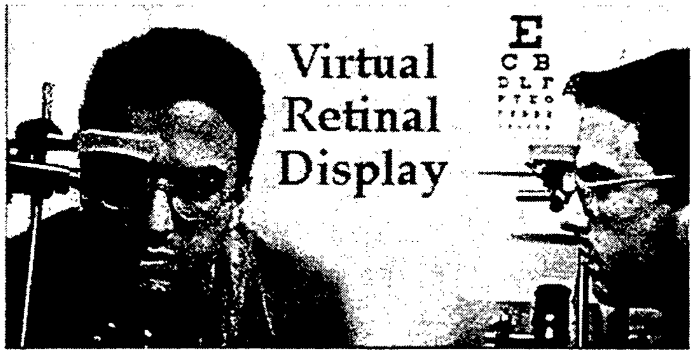

Figure 8: Virtual Retinal Display Prototype

3.1.3.1.6 Binocular Omni-Orientation Monitor (BOOM)

Fake Space Laboratories provides the BOOM3C with has two CRT's (1280 x 1024) mounted in a 6-joint, counterbalanced stand and a full-color head-coupled stereoscopic display. The BOOM3C provides high-quality visual displays and tracking integrated with a counterbalanced articulated arm for full six-degree of freedom motion (x, y, z, roll, pitch, yaw). Figure 10: BOOM Use With NASA's Virtual Wind Tunnel shows a BOOM system being used for NASA Ames' Virtual Wind Tunnel.

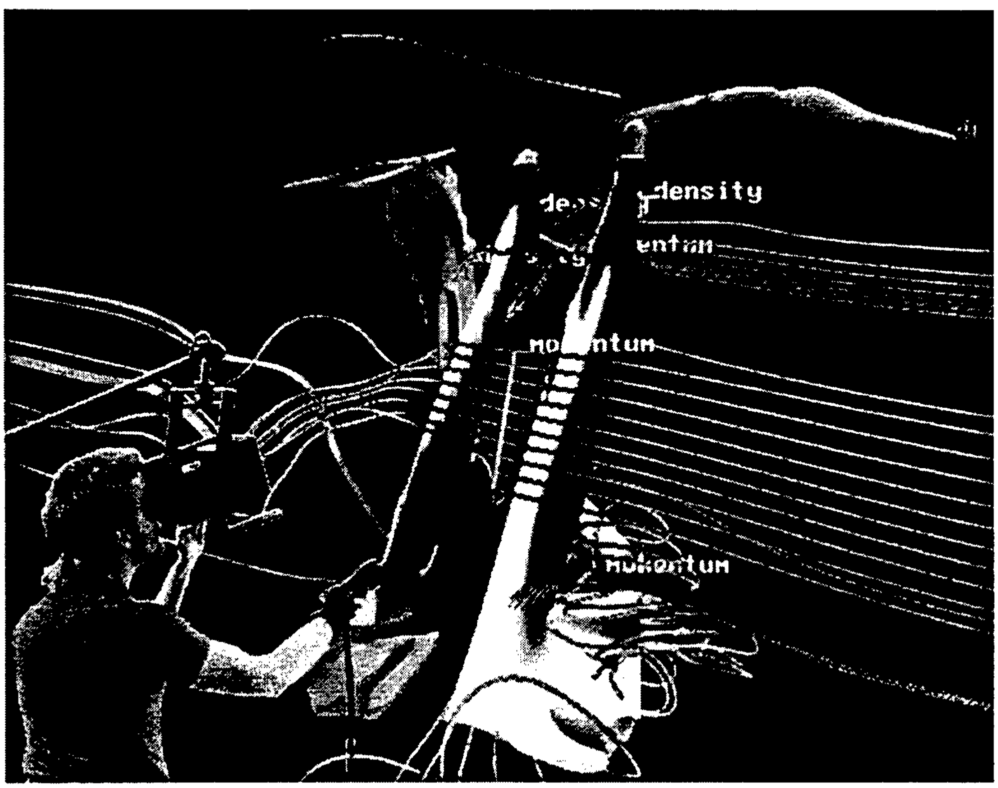

Figure 9: BOOM Use With NASA's Virtual Wind Tunnel

3.1.3.2 Sound

Sound systems must be able to generate sound in 3-D, which means sound can come from the left, the right, up, down, the front, the back or any combination. Additionally, environmental effects such as Doppler, and sound reflections off surfaces should be possible to reproduce using the sound system.

Important performance characteristics for 3-D sound systems are:

- Number of input channels - More inputs generally result in more realistic 3D sound.
- Type of System - Could be a PC board, a stand alone system, etc.

In addition, some developers are creating "cones of sound". One example is Virtual Audio Imaging (VAI), which is being marketed by Brown Innovations Inc (Brown Innovations, Inc., 1997). VAI is more than just a new product; it is a new technology. VAI is helping solve many problems associated with audio presentations in public areas. Conventional speakers broadcast sound in all directions which can be disturbing to everyone in the vicinity. It is difficult to hear sounds playing through speakers where there is a significant amount of ambient noise. Headphones have been the solution to sound isolation in the past although headphones wear out, are stolen, are socially isolating and impractical in many applications. This technology in audio reproduction transforms any recording into an isolated three-dimensional audio experience. Stand or sit under VAI to hear music, voices or sound effects in pure stereo perfectly in any ambient environment. Just two feet outside the intended listening area the sounds playing through VAI can barely be heard. Step away from the listening region and the sound level drops by over 80%.

Specially designed and positioned full-range electro-acoustic drivers project stereo sound waves onto the interior surface of an acoustic lens. This reflective surface focuses the sound waves directly into the listener's ears. This 3-D acoustic image is achieved without any computer processing. Figure 11: Virtual Audio Imaging Dome Hanging Above a Workspace shows an acoustic lens hanging at one of the demonstrations.

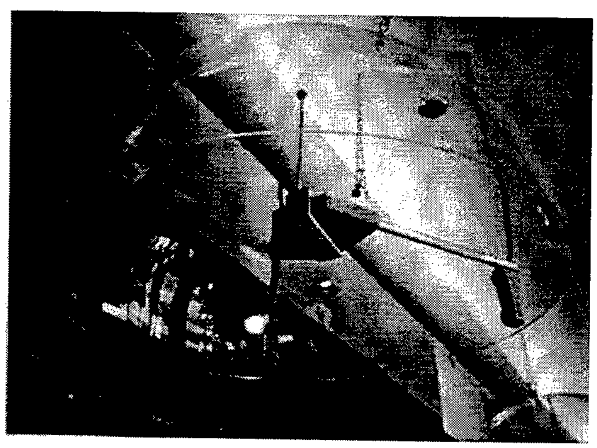

Figure 10: Virtual Audio Imaging Dome Hanging Above a Workspace

3.1.4 Input/Output Feedback

To get a true "feel" for being immersed, interactive feedback needs to be provided to the subject. There are various ways to do this, from actually physically restricting movement, to association of vibrations or other feedback, to coming in contact with an object. The next few paragraphs address these methods.

3.1.4.1 Tactile

Tactile systems are the simpler but sometimes less realistic method of feedback. They give the user the sense of actually touching a virtual object, but it doesn't necessarily give the user the sense that the object actually exists.

(For example, a person touches a virtual wall and although they can feel something like a vibration when they reach the wall, nothing prevents them from extending their hand on through the wall.) Tactile systems also often provide temperature feedback to the user. The systems are normally associated with a glove that the subject wears.

One example is the Virtual Technologies CyberTouch. The product, CyberTouch, consists of a tactile feedback option for the 18-sensor CyberGlove instrumented glove. CyberTouch features small vibrotactile stimulators on each finger and the palm of the CyberGlove. Each stimulator can be individually programmed to vary the strength of touch sensation. The array of stimulators can generate simple sensations such as pulses or sustained vibration, and they can be used in combination to produce complex tactile feedback patterns. Software developers can design their own actuation profile to achieve the desired tactile sensation, including the perception of touching a solid object in a simulated virtual world. Figure 12: Example of Tactile Feedback Gloves from Virtual Technologies is a photograph of the gloves with the stimulators (Virtual Technologies, Inc, 1997).

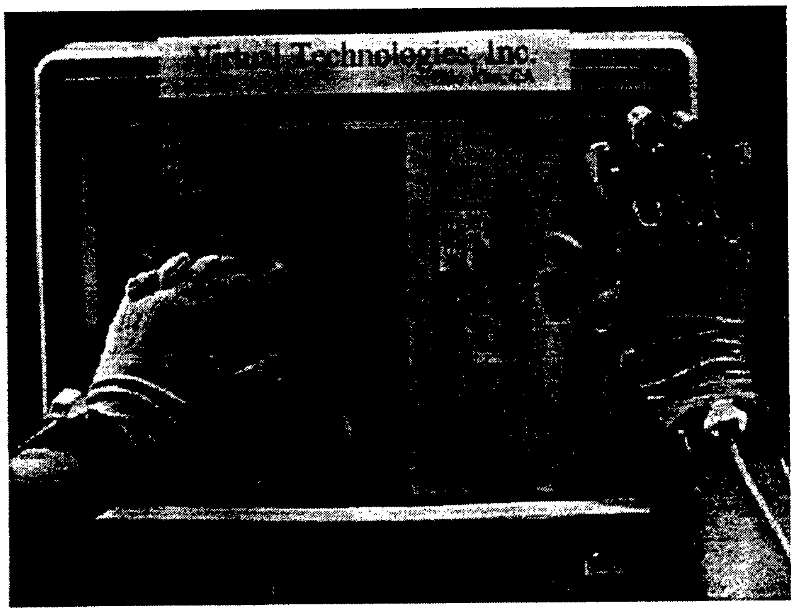

Figure 11: Example of Tactile Feedback Gloves from Virtual Technologies

3.1.4.2 Haptic

Force feedback systems use the sense touch, so that the user has the sense that the virtual object actually exists. (For example, a user touches a virtual wall, and the force feedback system doesn't allow them to go through the wall.)

Probably one of the most famous and now readily available haptic systems is the PHANToM which was developed at MIT and is now marketed by SensAble Technologies, Inc. It is limited in its radius of operation, but it is a very important first step in the development of haptic feedback devices. Below is a description of the PHANToM.

> "At the simplest level, the PHANToM design allows the user to interact with the computer by inserting their finger into a thimble. For more sophisticated applications, multiple fingers may be used simultaneously or other devices such as a stylus or tool handle may be substituted for the thimble.
>
> Research on touch, or haptic, computer interfaces, has been active for decades. The PHANToM, based on work done at MIT, represents a breakthrough in this research. The PHANToM is unique in that it offers realistic 3-D touch, the ability to feel the physical properties of virtual 3-D objects, with much higher fidelity and much lower cost than previous force feedback devices. The device's patented design allows:
>
> - High fidelity of 3-D haptic feedback
> - Ability to operate in an office/desktop environment

- Compatibility with standard PCs and UNIX workstations
- Universal design for a broad range of applications

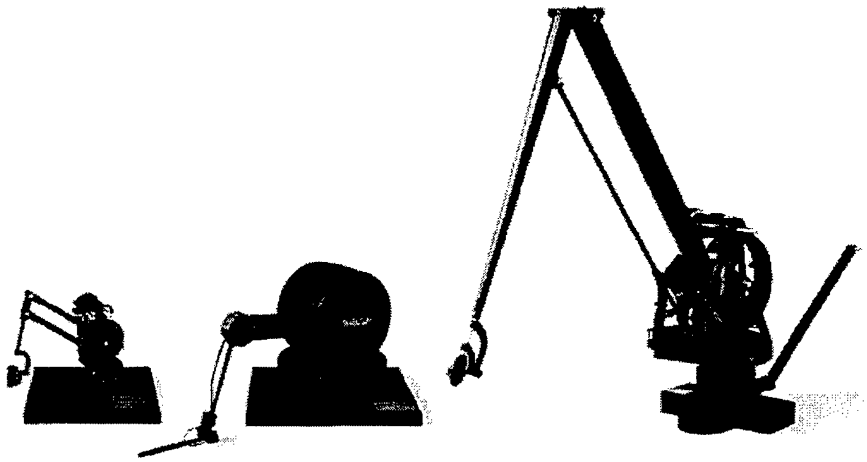

Figure 12: Three Models of the PHANToM

The PHANToM is distinguished from other touch interfaces by what it isn't. The PHANToM is not:

- A bulky exoskeletal device
- A buzzing tactile stimulator
- A vibrating joystick

The PHANToM provides 3 degrees of freedom for force feedback, and optionally, 3 additional degrees of freedom for measurement. Although haptic devices have been around for some time in research projects, the PHANToM is the first commercially available haptic device supporting standard computer platforms and an aggressive price point for a 3-D device of such quality and fidelity.

A fully configured PHANToM system includes the PHANToM Haptic Interface, thimble or stylus, Power Amplifier, computer adapter, cables and software libraries. The standard interface between the PHANToM Haptic Interface and the computer is via an ISA/EISA card, with device support for MS/DOS, MS/NT and SGI/IRIX (VME is optional, see below). There are two standard PHANToM models for the desktop, which vary in the size of workspace supported. Both are available with or without an Instrumented Gimbal. With the addition of an Instrumented Gimbal in place of the passive gimbal 3 rotational degrees of freedom (pitch, roll, and yaw) can be measured. This provides a system capable of 6 degrees of freedom input and 3 degrees of freedom output. The specifications extremes for the smallest and largest are as follows:" (SensAble Technologies', 1997).

Table 3: PHANToM Technical Specifications

	Standard	**Super Extended**
Nominal position resolution	860 dpi	>1000 dpi
Workspace	5x7x10 in	16x23x33 in
Backdrive friction	0.15 oz.	0.75 oz
Maximum exertable force	1.9 lbf	4.9 lbf
Closed loop stiffness	20 lbs/in	5.7 lbs/in
Inertia (apparent mass at tip)	<0.17 lbm	<0.34 lbm
Footprint	7x10 in	8x8 in

3.1.4.3 Hybrid System Under Development

Graphics Systems Development Corporation (CSDC) of Mountain View, CA is currently working on a hybrid system for the U.S. Army Simulation, Training, and Instrumentation Command (STRICOM). The development is a Phase II Small Business Independent Research project. The following description is from the Web site and shows the novel approach of the Touched Objects Positioned In Time (TOPIT) project:

> "The object of the project is to build a prototype virtual cockpit that includes force and tactile feedback. The user wears a head mounted display that presents stereo imagery of a cockpit interior, including the instrument panel, as well as the out-the-window scenery. A representation of the user's hand is also rendered in the scene. The user may actuate a variety of controls on the instrument panel, and can accurately feel the forces and surface textures of the controls. The simulator can be reconfigured entirely in software to represent different cockpits...
>
> ...The feel of the instrument panel controls is provided by a servomechanism device that places actual physical controls in their correct positions, orientations, and configurations. A tracker and data glove continually provide the position of the user's hand and fingers to a computer. The computer extrapolates the user's hand position as the user reaches for a control. Using the extrapolated data, the computer commands the servomechanism system to place the correct type of control in the correct position to be actuated. The servo system has a "touchpanel" that contains examples of a dozen or so different types of controls, such as toggle switches, knobs, and push buttons, that are used repeatedly to represent any number of instrument panel controls. Because the visual representation of controls is accurate and because it is difficult to recognize an object by touch alone, a relatively small number of examples of controls suffices for many instruments. The touchpanel portion of the system may be interchanged for further flexibility. The touchpanel is driven by servo mechanism that place switches and rotary controls in their correct orientations to correspond to the particular control on the virtual panel, with programmable détentes and stops provided for rotary switches.

Figure 13: Artist Concept of Final TOPIT Configuration

A key aspect of the system is building a servo system that moves fast enough to have the control in place before the user's hand reaches it. Another key aspect is achieving precise low-latency tracking of both the user's head and the user's hand. The tracking must be accomplished in the presence of the moving metal elements and the electric motors of the servo system; a hybrid magnetic/inertial tracker was developed to meet the requirements. The tracker uses a Kalman filter to combine accelerometer, angular rate sensor, and magnetic tracker data. To minimize magnetic interference, the moving mechanism is built of non-magnetic stainless steel, and the main servo motors are kept distant with the use of cable drive mechanisms. The design objective is to have the switch panel move at 100 inches per second with 4 g's of acceleration along with a positioning accuracy of about 0.01". The final payload is somewhat heavier than originally intended, but performance is nonetheless close to these levels, and in any case capable of supporting typical control panel applications.

The system uses three computers: an SGI Onyx/RealityEngine2 that does the imagery, a Pentium-based PC that does the tracking, and a VME-based servo control system. Software was custom written for the device. The software for running the image generator is written using Silicon Graphics' Performer as a starting point. Software in a Personal Computer runs under a real time operating system called QNX. The tracking, switch selection logic, and high level control logic is performed in a PC to lower costs and to simplify interfacing with other image generators. The databases for the cockpit and environment were developed using MultiGen. Custom servo control software resides in the dedicated controllers in the VME system.

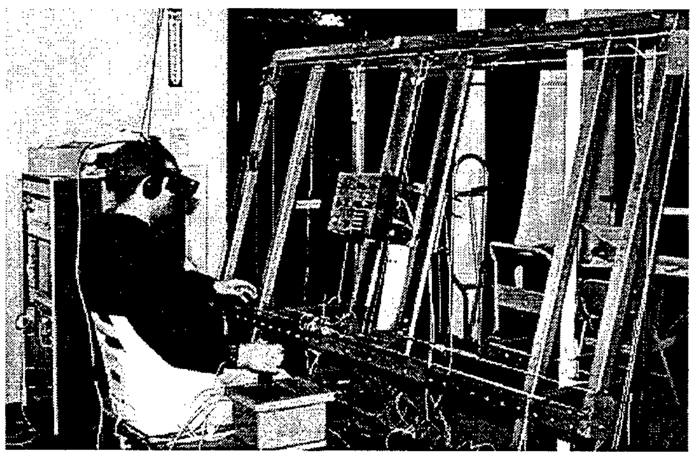

Figure 14: Recent Photo of TOPIT Prototype

The system provides high fidelity in reproducing force and tactile feedback for instrument and control panel environments.. Unlike systems carried on the user's hand, the positioned objects provide external forces and torques. A limitation of the approach, however, is that it only lends itself to a limited class of problems, such as control panels, in which there are relatively few types of touched objects and the objects are small enough to be moved rapidly into position to be touched...

...The system is expected to be useful for the development of instrument panels for aircraft and for automobiles, for industrial control panel design, and for aircraft and other types of simulators. Although final pricing has not been set, we estimate a selling price of $200K for the TOPIT mechanism, servo controller, tracking computer, tracker, and instrumented glove. An image generator and head mounted display will be available at additional cost, roughly $100K, but depending upon image generator choice and display resolution. The active area of the TOPIT device can be varied in follow-on units without too much difficulty." (CGSD Corporation, 1996).

3.2 Software

Outside of the operating systems and drivers for the various input/output devices, there are two main software components that are important in the VR realm: the environments and the human figure models (HFMs). The next paragraphs will identify some of the software available to handle these requirements.

3.2.1 Environments

Visual databases serve to create the graphics that are shown on the displays for virtual environment systems. They are interactive, and allow the user to create, edit, and view 3-D, fully-textured scenes and instrumentation. Many contain object libraries, in which a standard part or object can be pulled form the database and displayed on the screen. A capability to look for is the number of formats of other CAD/CAM data that can be imported and displayed. Important performance categories for visual databases are:

- Model Switching (Limited detail switching) - Need more detail on objects that are close to the user's viewpoint.
- Object libraries - Objects can be made and saved in the object libraries, or they can be purchased from companies that specialize in making different objects.

Some of these environment generators, such as MultiGen Inc., have realized the ease of use these visual databases provide. SmartScene™ is a product from MultiGen Inc. which allows a user to "stand" in the scene he or she is creating and design a realtime 3D world. SmartScene™ is described below:

> "Instead of modeling objects polygon by polygon with a mouse and keyboard, the SmartScene user easily and rapidly assembles and manipulates realtime 3D scenes in a fully immersive virtual reality environment. Wearing pinch gloves and a 3D head-mounted display, the SmartScene user steps into a virtual workspace and becomes the architect of realtime 3D worlds through the intuitive and natural movements of a two-handed interface.
>
> Pre-modeled components accessed through SmartScene are embedded with authoring functions and tools, making the assembly of a realtime 3D scene a "building block" process. The user easily plucks a recognizable component from a library of models created with MultiGen tools, snaps it into the scene, and then customizes the size and appearance of the model. SmartScene models are "smart" because they are encoded with context-appropriate choices and behaviors: not only do they precisely align themselves with other objects in the scene, they also seek out appropriate components to snap onto. For example, trees can be inserted into grassy areas, but not into paved spaces."

This interface would eliminate a significant amount of training for scene generation personnel. However, there might be trade-off of possible simulator sickness for extensive use of the HMD if there was prolonged usage. The software is now commercially available.

3.2.2 Human Figure Models

There are various HFMs available from different sources, each with its strengths and weaknesses. The more anthropometric detailed ones take more system resources to run, but return more detailed information. The less detailed HFMs take less space and run faster, but the level of information revealed is less comprehensive. Of these, the University of Pennsylvania's *Jack* is one of the more detailed and commonly used HFMs. This software is now under the commercial marketing and technical support control of Transom Technologies, Inc. as Transom Jack V1.1. The next most detailed and moving up in acceptance and use is the McDonnell Douglas Human Modeling System (MDHMS).

Figure 15: Examples of (a) Transom Jack and (b) MDHMS Human Figure Models

3.2.3 Integrated Systems

The placement of the HFM within the 3-D environment and its independent animation or tie to a real-time person immersed in a virtual environment is a product of integrated virtual environment systems. Of course there is the DEPTH program developed by Hughes Missile Systems Company, the prime contractor to Armstrong Laboratory on the DEPTH contract. It integrates the various versions of *Jack* and Transom Jack HFMs into the DEPTH virtual environment. In addition to DEPTH, Division Inc. and McDonnell Douglas Aerospace Corp. signed an agreement in March 1996 that gives Division exclusive worldwide distribution rights for the McDonnell Douglas Human Modeling System. This allows for full integration of MDHMS with Division's dVISE software for creating virtual worlds.

4. "PRESENCE" IN VIRTUAL ENVIRONMENTS

As seen in the previous sections, the capability currently exists for immersion into virtual environments. However, the ultimate goal of immersion into a virtual environment is a feeling of presence in that environment. When "presence" has been achieved, you feel that you have experienced something, not just viewed it. But do we need to achieve total presence for all supported activities? No, the degree of presence necessary, like everything else, is dependent upon the task that the virtual system is being used for. If there is a team of people standing together and doing a collaborative design analysis, there isn't the need for a total sense of presence. The team will be discussing and interacting with the other team members and will require a lower level of immersion so presence isn't an issue. A virtual workbench viewing system would suffice for the team. However, if you are analyzing a detailed maintenance task by doing a run through of the task, a higher level of presence is desired. Differing forms of maintenance training would require different levels of presence. The analysis of a task normally done in a "calm" depot level arena would not require the same level of presence as practicing "hot rearming" in a quick combat turn at the end of a runway with engines running. The interrelationship of these functions.and the distinction between immersion and presence is explained in understandable terms by Mel Slater, et al. in *DEPTH of Presence in Immersive Virtual Environments", Presence: Teleoperators and Virtual Environments.* The following is an excerpt from Section 2 of the paper (Slater, Usoh, & Steed, 1995):

> Immersion refers to what is, in principle, a quantifiable description of a technology (Slater, Usoh and Steed, 1995). It includes the extent to which the computer displays are extensive, surrounding, inclusive, vivid and matching. The displays are more ***extensive*** the more sensory systems that they accommodate. They are ***surrounding*** to the extent that information can arrive at the person's sense organs from any (virtual) direction, and the participant can turn towards that direction receiving the appropriate directional sensory signals. The notion of surrounding also includes the greater the reproduction of the natural modes of sensory presentation (visual and auditory stereopsis for example). They are ***inclusive*** to the extent that all external sensory data (from physical reality) is shut out. Their ***vividness*** is a function of the variety and richness of the sensory information they can generate (Steuer, 1992). Vividness is concerned with the richness, information content, resolution and quality of the displays. Finally, immersion requires that there is ***match*** between the participant's proprioceptive feedback about body movements, and the information generated on the displays. A turn of the head should result in a corresponding change to the visual display, and, for example, to the auditory displays so that perceived sound direction is invariant to the orientation of the head. Matching requires body tracking, at least head tracking, but generally the greater the degree of body mapping, the greater the extent to which the movements of the body can be accurately reproduced.
>
> Immersion also requires a self-representation in the VE - a Virtual Body (VB). The VB is both part of the perceived environment, and represents the being that is doing the perceiving. Perception in the VE is centered on the position in virtual space of the VB - e.g., visual perception from the viewpoint of the eyes in the head of the VB, an egocentric viewpoint.
>
> Our general hypothesis is that presence is an increasing function of two orthogonal variables. The first variable is the extent of the match between the displayed sensory data and the internal representation systems and subjective world models typically employed by the participant. Although immersion is increased with the vividness of the displays, as discussed above, we must also take into account the extent to which the information displayed allows individuals to construct their own internal mental models of reality. For example, a vivid visual display system might afford some individuals a sense of "presence", but be unsuited for others in the absence of sound (Slater, Usoh and Steed, 1994). The second variable is the extent of the match between proprioception and sensory data. The changes to the display must ideally be consistent with and match through time, without lag, changes caused by the individual's movement and locomotion - whether of individual limbs or the whole body relative to the ground.

Given that background information, without going into the details of the experiment, the following are some of the conclusions that were drawn:

- Presence is concerned with how well a person's behavior in the VE matches their behavior in similar circumstances in real life, rather than with how well they perform as such.
- Increased immersion (egocentric rather than exocentric viewpoint, and greater vividness in terms of richness of the portrayed environment) do indeed improve task performance.
- Reported presence was higher for egocentric compared to exocentric immersion, but that presence itself was not associated with task performance.

These are just some of the points of the paper, which is excellent reading for the relationship between immersion and performance based training with good references. Another associated paper found on the web on the subject is *Factors Affecting Presence and Performance in Virtual Environments* by Woodrow Barfield and Claudia Hendrix of the University of Washington.

5. SIMULATOR SICKNESS

Anyone who has played a 3D simulation game with excessive movement of the visual cues such as in Wolfenstein 3D has probably experienced simulator sickness even in a non-immersed environment. This type of simulator sickness is caused by a cueing conflict between the eyes seeing movement on the monitor, but the inner ear not sensing any motion of the body. One of the major problems that will need to be overcome in immersive environments is that of possible simulator sickness. A study by Crowley in 1987 showed that once someone has had simulator sickness, there is the high likeliness that they will take steps to avoid the same environment that caused it.

There are various papers and reports on the Web addressing simulator sickness and some of it causes. One of these that is easy to read and understand is by Mark Draper, dated April 29, 1996 and titled *Can your eyes make you sick?: Investigating the Relationship between the Vestibulocular Reflex and Virtual Reality.* The Vestibulo-ocular Reflex (VOR) is a primitive eye-movement reflex that stabilizes visual functions to keep images stabilized on the retina during movement of the head. The paper then describes other tacking eye movements and how they relate to the VOR. Next, it describes the concept and characteristics of simulator sickness, and the sensory conflict theory as a potential link between the visual and vestibular systems and simulator sickness. Finally, an annotated list is presented of current-technology virtual interface artifacts that may also contribute to simulator sickness, along with the associated rationale (Draper , Mark H., 1996).

A report for the U.S. Army Research Institute for the Behavioral and Social Sciences titled *Simulator Sickness in Virtual Environments* (Kolasinski, et al., 1995) addresses some new theories in the cause of simulator sickness. The goal of the report was to identify factors involved in simulator sickness in virtual environments so that such sickness can be avoided or, at least, its severity and duration reduced. The following excerpts are some of the highlights of the report:

> "To emphasize the significance of simulator sickness, Crowley (1987) identified four important aeromedical and operational consequences: decreased simulator use, compromised training, ground safety, and flight safety. Decreased simulator use may result from pilots who have experienced symptoms and are unwilling to repeat the experience. Training may be compromised in one of two ways. First, symptoms in the simulator may distract the pilot during the session, thus interfering with the training process. Second, pilots may adopt behaviors to avoid symptoms in the simulator which, if transferred to the actual aircraft, may be detrimental. Ground safety in terms of exiting the simulator or driving away from the site may be jeopardized by aftereffects from the simulator such as postural disequilibrium (ataxia) and flashbacks. Such aftereffects, along with any adaptive behaviors (which may have negative transfer effects), may also compromise flight safety after simulator exposure.
>
> In an analysis of data from ten U.S. Navy and Marine Corps flight simulators, Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley (1989) found that approximately 20% to 40% of military pilots indicated at least one symptom following simulator exposure. McCauley and Sharkey (1992) pointed out that pilots tend to be less susceptible to motion sickness than the general population due to a self-selection process based on their resistance to motion sickness. Since VE technologies will be aimed at a more general population, such selection against sickness may not occur. Thus, McCauley and Sharkey suggested that sickness may be more common in virtual environments than in simulators.
>
> McCauley and Sharkey (1992) also noted that commercial users of VE systems may differ from the typical user of a military flight simulator in terms of their physical and psychological state. Some commercial users may be under the influence of medications, drugs, or alcohol. It is possible that such substances may increase susceptibility to sickness.
>
> The theory of cue conflict is the most widely accepted theory of simulator sickness. Cue conflict occurs when there is a disparity between senses or within a sense. The two primary conflicts thought to be at the root of simulator sickness occur between the visual and vestibular senses. In a fixed-base simulator, the visual system senses motion while the vestibular system senses no motion. Thus, according to the cue

conflict theory, a conflict results. In a moving-base simulator, the visual stimuli experienced may not correspond exactly to the motion which the vestibular system registers. Thus, a conflict can still result.

A major effect of simulator exposure is postural disequilibrium, or ataxia. Thomley, Kennedy, and Bittner (1986) suggested that ataxia is due to a disruption in balance and coordination resulting from the visual and vestibular adaptation to conflicting cues occurring during simulator exposure."

This report presented three global categories of factors-subject, simulator, and task-that may be associated with simulator sickness in virtual environments. Many factors were identified in each of these categories. The factors, as well as their known effects on simulator sickness and predicted effects on sickness in virtual environments, were summarized.

Factors within the three categories were listed in alphabetical order. This gave equal importance status to all of factors instead of implying that some factors are "above" or "below" others on some type of scale. Furthermore, the alphabetized list simplifies use in a reference capacity. For more detail on a particular factor, each entry refers to a sub-section in either the individual, simulator, or task sections.

6. CURRENT TECHNOLOGY EFFORTS

The following paragraphs are some of the ongoing technology development efforts at different locations. They cover the military and civilian developments, however they are in no way a complete listing. These are just some of the Web sites found regarding some of the key technologies required for an immersive environment program. There are three areas which seem to have the largest hurdles to overcome in order to achieve "fully immersive" realization: body tracking, haptic feedback, and lag.

6.1 Biodynamics & Biocommunications Division (AL/CFB)

The Biodynamics & Biocommunications Division (AL/CFB) is currently working in the area of human sensory feedback. Below is detailed information about the Human Sensory Feedback (HSF) for Telepresence Project from AL/HRG (McDaniel, 1996)

"Motivation

Many circumstances require that work be done in environments that are inaccessible or too dangerous for humans to enter. These environments may be under water, in space, or contaminated by nuclear, biological, or chemical agents. The work requires humans to extend their reach into the forbidden environment. These tasks may often be accomplished with telerobotic manipulators whose motions are directly controlled by human operators. Telerobotic systems provide a safe, controllable ability to assess and perform tasks while remaining distanced from the area. Sensory feedback responses and dexterous, manipulative end-effectors enable operators to complete tasks as if they were actually at the site. To the degree that the telerobotic system makes the operator forget about the intervening system between him and the task and feel present at the remote site, telepresence has been achieved. Because of the varying and unforeseen nature of the tasks at the work site, a robot cannot simply be programmed to complete them. Human cognitive skills are required to ensure completion of the tasks. Telerobotics is currently the only solution.

Mission

Investigate sensory-rich, human-in-the-loop control of telerobotic systems. Define performance measures for HSF that will evolve into design criteria for advanced development. Validate the telepresence and HSF concepts and measures via in-house laboratory experimentation and testing. Use laboratory results to develop HSF databases for use in the formulation of specifications for advanced designs and developments."

Although the focus is toward telepresence and robotics, a virtual environment could be substituted for the real surroundings. The most difficult part of the program is the feedback to the operator to establish the realistic telepresence. The following paragraphs from the same Web site address these issues, and the HSF projects goals:

"Research Activities

Overview

A complete telerobotic or telepresence system typically includes four major components of sensory feedback from the remote (or virtual) site to the human operator: visual, aural, force (kinesthetic), and tactile. It is common practice to ignore the possible feedback components of smell (olfaction) and taste. Aural feedback technology is mature and available commercially. Since many other groups are conducting enormous research in visual image synthesis and display technology, the HSF project focuses its attention on the force and tactile feedback components which are the least understood and most challenging of all the telerobotic system components. Force feedback is divided into two areas with distinctly different technology requirements: coarse manipulation and fine manipulation.

Coarse Manipulation

The HSF program conducts exploratory research into the feedback mechanisms required for the coarse positioning of robotic end-effectors using robotic arms under direct human control. The role of force feedback is gauged to determine acceptable methods by which force information at the work site can be presented, nonvisually, to the telerobotic operators. Under the domain of coarse manipulation, the primary research initiatives are to explore the use of virtual fixtures to improve teleoperator system performance. The experimental work is conducted on three primary devices: the Haptic Joystick Controller, the Force-REFLecting EXoskeleton (FREFLEX) and the PHANToM(TM). An exoskeleton is a device worn by a human which attaches to the arm and/or hand and which measures the operator's movements so they can be mimicked by a remote manipulator. A force-reflecting exoskeleton can additionally make the operator feel the forces measured by the remote manipulator.

Fine Manipulation Research

Fine manipulation is required to accomplish tasks designed for human hands. Dexterous, multifinger robot hands teleoperated by hand-master devices offer much more capability than simple parallel-jaw grippers. The HSF effort focuses on cooperative outside research in fine manipulation, and supports innovative motor technology development for application to hand-size multifinger force-reflecting exoskeletons. Figure 17 is an artist's rendering of the HSF Vision.

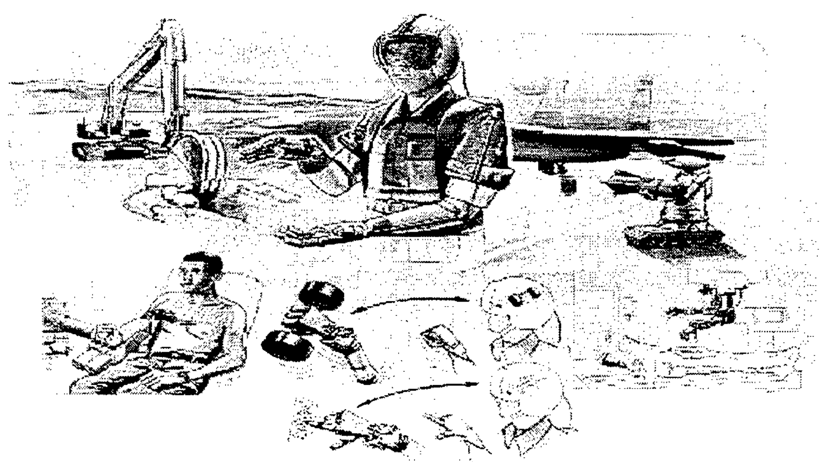

Figure 16: Artist's rendering of the HSF Vision

Tactile Feedback Research

Tactile feedback is vital to achieving a full sense of presence and to manipulating the remote or virtual environment with dexterity. Even though considerable research exists on the psychophysiology of human touch, the development of mechanical aids to stimulate this sense realistically has continued to be a serious challenge. Tactile feedback requires the development of hardware displays that are light weight, portable, and suitable for mounting in gloves. The HSF team is currently concentrating its efforts on the use of tiny wires (tactile stimulation arrays) which vibrate under the user's fingertip in response to commands from the computer as it generates the virtual environment. The lab's HAPtic-TACtile (HAPTAC) and Tactile Graphics (TacGraph) systems provide practical application of the technology."

Due to the commonality of goals, and proximity to HRG, this is an effort worth working closely with and could result in substantial savings. It could also result in stronger funding advocacy due to the partnership and technology transfer among "sister organizations".

6.2 Aircrew Training Research Division (AL/HRA)

The Aircrew Training Research Division in Mesa, AZ is also performing exploratory and advanced development work on aircrew training devices. AFRL/HEA supports two of the Air Force's primary research and development objectives by advancing aircrew training system technology and by evaluating the training effectiveness of that technology. This is accomplished by developing and evaluating new training methodologies and engineering concepts that can provide increased aircrew training at lower cost. The division then uses these new technologies to improve aircrew performance over a wide range of areas of critical interest to training specialists and simulation engineers. Some of the technologies that are being used for AFRL/HEA's work could be transfered and reintegrated into the immersion technology effort. This is just based upon the information found on the web, a visit to the actual location would prove beneficial. (Irwin, et al., 1997)

6.3 University of Washington Human Interface Technology Lab

One of the technology development sites that were actually visited was University of Washington Human Interface Technology Lab (HITL). They are doing diverse activities in the area of human/machine interfacing, especially in the realm of VR. They are also doing preliminary design of 2D and 3D haptic interfaces and as previously mentioned, VRDs. Their proximity to Boeing makes them a likely partner with that company in the development of various technologies for the aerospace industry, including maintenance. The home page is at URL: http://www.hitl.washington.edu/ with links to it projects, people, consortium, and publications. It is a good starting point for information on their varied activities. (HITLab, 1997)

6.4 NASA Ames Research Center

Another location that was actually visited was NASA Ames Research Center. NASA Ames has an experienced staff in VR technology in numerous disciplines and the following are just some of their efforts:

- Virtual Window Design(Navigational Displays)- synthetic perspective displays to supplement the traditional optical windows used for guidance and control of aircraft on the ground as well as in the air.
- Video Eye Tracking- not a real-time tracking, but very cheap and very accurate.
- Image processing- a stereo image compression method to increase the quality of the image without increasing the amount of computations needed.
- 3D Audio Augmentation- auditorily spatialize the channels an air traffic controller is responsible for to improve communication.
- VR Lag- testing the latency and image update rate of current tracking technology (Ascensions' Flock of Birds & Polhemus' Fastrak) and their influence on VR immersion perception.
- Virtual Wind Tunnel- used to visualize and evaluate different Aerospace properties of aircraft data that has been gathered in the wind tunnel or through Computational Fluid Dynamics (CFD) computations.

Additional general information on some of Ames' efforts can be found on the web at URL: http://duchamp.arc.nasa.gov/adsp.html. Ames' home page is at URL: http://www.arc.nasa.gov/. (NASA Ames Research Center, 1997)

6.5 U.S. Army Research Institute - (ARI)

The prime site for review is in the Army under its Simulation Training and Instrumentation Command (STRICOM). It is ARI's Simulator Systems Research Unit (SSRU) located near Orlando FL. Their work would be very beneficial in the human factors part of the immersion efforts because of their previous work on simulator sickness in virtual environments. STRICOM has had a part in the development of VR interface equipment such as the ODT previously described in section 3.1.2.5. SSRU's web site is at URL: http://205.130.63.3/ssru.htm (SSRU, 1996) and STRICOM is at http://www.stricom.army.mil/ (STRICOM, 1997).

7. SUMMARY

Virtual reality has come a long way since the turn of the decade and is continually growing, with extensive research by commercial, government, and educational agencies. On the other hand there are still hardware and software issues that need to be overcome before virtual "presence" is truely felt. One issue is simulator sickness. The inner ear can not feel the translation motion unless it is physically experienced. The treadmill is possibly effective in decreasing the degree of simulator sickness because it decreases the FOV speed to that of walking or running. Also it is a more realistic interface with the environment than a 3D mouse or joystick. Presence in a virtual environment will also benefit greatly from haptic, not just tactile, feedback. When you do not need to interpret one sensory feedback to represent something else, a truer presence will be accomplished. Another problem is in multi-person tasks where peripheral vision plays a major role in the accomplishment of the task and knowing the location of the other person is. Currently the HMDs have FOV limitations that can be restrictive for multi-person tasks.

What issues need to be resolved to give the feeling of presence for immersion?

1. Lag. This is a hardware and software issue that affects various senses, but primarily the visual sense, causing cue conflict. The lag can start at the position sensor interface to the computer, continue through the processor, and culminate in the presentation device. This is a known problem in the VR world, and attempts are being made to lessen it to a tolerable level with increased throughput.
2. Haptic interfaces. The PHANToM is a step forward for limited uses, however, a more comprehensive system needs to be developed for a complete sense of immersion. A haptic body suit needs to developed that is not too cumbersome.
3. Position sensor performance. Position sensors are a mainstay of the VR realm and are very sensitive instruments. Their sensitivity also leads to problems with their effective ranges and interference from other devices. Each type of sensor has its advantages and shortcomings, so a hybrid of technologies might need to be promoted to overcome the problems.
4. Visual displays. The egocentric immersion uses HMDs. Again, there have been great strides made in HMD capabilities, but currently they still have either a low resolution or a narrow field of view. If those issues are overcome, the HMD weighs too much. This weight might also be a contributing factor to simulator sickness.

Can we make effective use of VR and not be immersed? Yes, there are other effective uses of the VR technology available today. You can be immersed with today's technology, and not make many fast movements causing simulator sickness. But you cannot expect to feel total presence; you have to be prepared for "work around" interfaces. For example, a blinking virtual object may mean it is being held or a buzzing on your hand may mean contact with another object.

As mentioned previously in this report, different requirements dictate different effective environments for the task at hand. Does each person need to be individually immersed or can a SID be effective for the design evaluation? For a collaborative design evaluation you don't want everyone going off on a tangent, you need to keep them focused. This might be better accomplished by a Virtual Workbench or CAVE type of visual environment. Are you looking for a true sense of presence in doing a task for time studies, or do you want to just "go through the motions" of the task to make sure that it is possible to do? When the need is an egocentric environment for evaluation or training, an immersed environment is more appropriate. The degree of immersion is also task dependent. Does the normal task require a lot of locomotion to various places or is it primarily in one location? Does the task normally require access to an item that requires an unusual posture or reach? How realistically do you want/need these working limitations presented?

There is an abundance of work being done in VR by government, commercial and educational agencies. The U.S. Army Research Institute for the Behavioral and Social Sciences, (ARI) is doing extensive work in VR training at the Simulator Systems Research Unit (SSRU) at Orlando FL. Joe Psotk, a member of the the ARI team, has done work in virtual reality immersion training. Various NASA Centers are doing work distributed Virtual Environments for learning and practicing task for Space Shuttle and Space Station missions. NASA Ames is challenging the problem of lag times in VR by trying to minimize it down to an acceptable level. Since we have a problem with virtual lag here in the same room, imagine the lag time trying to control an item in Mars. In addition, AL/CFB is doing work in telepresence at Wright-Patterson AFB, Ohio.

Commercially there is work being done by Boeing Aerospace in the area of haptics and other VR issues in cooperation with the University of Washington in haptics and other VR issues. Boeing is also are doing independent work on exoskeleton and robotic graphics VR simulators. A possible merger with McDonnell Douglas Aerospace, there is sure to be strides made in VR research and development in manufacturing and maintenance simulations.

The entertainment industry is also helping to "drive" processor speeds and interface capabilities up and prices down. The leisure customer is no longer happy to have Nintendo type of games and simulations anymore. They want to escape their world, be immersed, and entertained. The days of the joystick and 12 inch monitor with 2D graphics are over. At SIGGRAPH 96, almost half of the exhibitors had some connection with the entertainment industry.

The University of Washington is challenging the quests of human interfacing to machines and in virtual environments. Their goal is "to transform virtual environment concepts and early research into practical, market-driven products and processes. HITL research strengths include interface hardware, virtual environments software, and human factors. The Lab hopes to develop a new generation of human-machine interfaces to provide solutions to challenges in a variety of domains."

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9. APPENDIX: VIRTUAL ENVIRONMENT EQUIPMENT AND VENDORS LIST

9.1 Host Computer

The host computer is normally a PC that serves to link all of the components in the virtual environment system together. It gives commands to the image generator, sound system, and force feedback system, and receives input from the trackers and data gloves. Since it doesn't take an incredible amount of computing power to perform these functions, a normal Pentium PC should be sufficient to serve as the host computer.

Current state of this technology: Pentium PC's are currently capable of handling host computer responsibilities.

9.2 Image Generator (IG)

An image generator is a digital electronic system for producing sequences of video images in real time. The IG uses a digital database of graphics objects to produce images that are sent to display devices. There are both low-cost and high-cost IGs, but for sophisticated applications, a high-cost IG is a must.

The image generator system is composed of the following components; an IG host, a geometry processor, a pixel processor, and a video processor. (Note: the names of these components vary depending on brand name, but the functions remain the same.) The IG host is basically a computer that talks to the host computer. The IG host also performs database retrieval duties, as well as controlling special-purpose hardware. The geometry processor converts 3-D polygons into to 2-D perspective polygons as seen from the current eyepoint. The pixel processor converts the polygons to pixels, and typically requires the most computing power, about 10 GFLOPS. The video processor converts the pixels to video, and sends the video to a display device.

Important performance categories for IGs include:

- Polygon capacity - The number of polygons that can be generated per second by the IG.
- Update rate - The frequency with which the IG calculates a new picture.
- Transportation delay - The lag time, or number of frames delay, of the IG when a new eyepoint position is received from the user interface. (Should be no longer than 2 frames)
- Texture memory - the amount of texture memory on-line relates to the number of different texture maps which can be used to add variety to the scene.
- Anti-Aliasing - the ability to remove jagged edges on bitmapped displays by interpolating neutral colors or intermediate intensities.

Current state of this technology: IGs are still about three years away from to completely living up to the expectations of the VE community. For every image generator, there is usually only one application to which the device is ideally suited.

9.2.1 SGI Infinite Reality Engine (R10000)

Cost: $225,000

Vendor
Silicon Graphics Computer Systems
2011 North Shoreline Boulevard
Mountain View, California 94043
Point of contact: John Burwell
Phone: 415-933-1743 Fax: 415-964-8671

Specifications
Polygon capacity: 3 - 4.5 million polygons per second
Update rate: Can support up to 120 Hz, typically operates at 60 Hz.
Transportation delay: 33.3 msec at 60 Hz, which equals two frames.
Anti-Aliasing: Supports high-quality, multi-sample anti-aliasing.

Applications
Many companies are using SGI Infinite Reality Machines for the development of virtual environments. An example of this is CTA, Inc's, Mission Simulator System. The Mission Simulator System is a real-time, reconfigurable, man-in-the-loop simulator for commercial and military aircraft and other vehicles. The MSS is in use today as the core component of realistic flight training devices and as a prototyping tool used to explore aircraft, cockpit, C3I, and avionics system designs.

Maturity Level of SGI Infinite Reality Engine (R10000)
This IG has already been developed. As it stands, this is the most powerful image generator on the market today.

9.2.2 SGI RealityEngine^2

Cost: $94,000

Vendor Information
Silicon Graphics Computer Systems
2011 North Shoreline Boulevard
Mountain View, California 94043
Point of contact: John Burwell
Phone: 415-933-1743 Fax: 415-964-8671

Specifications
Polygon capacity: 180,000 - 270,000 polygons per second.
Update rate: Can support up to 120 Hz, typically operates at 30 Hz.
Transportation delay: 49.9 msec at 30 Hz, which equals 1 ½ frames.
Anti-Aliasing: Supports high-quality, multi-sample anti-aliasing.

Applications
Many companies are using SGI Reality Engine^2 Machines for the development of virtual environments.

Maturity Level
This IG has already been developed.

9.2.3 R3D/PRO-1000

Cost: $75,000

Vendor Information
Real 3D (a Lockheed Martin Company)
12506 Lake Underhill Road
Orlando, FL 32825-5002
Point of contact: John Lenyo
Phone: 407-826-3360 Fax: 407-826-3358

Specifications
Polygon capacity: 750K polygons per second
Update rate: Operates at 60 Hz.
Transportation delay: 56 msec at 60 Hz, which equals 3+ frames.
Anti-Aliasing: Supports real-time anti-aliasing.

Applications
R3D/PRO-1000 offers simulation and training professionals an unmatched price/performance package for an array of applications, including ship handling, flight simulation, driver training, rail training, and location-based entertainment.

Maturity Level
This IG has already been developed. This IG is cheaper than the SGI Infinite Reality Engine, but the performance isn't nearly as high.

9.2.4 ESIG-4500

Cost: $200,000

Vendor Information
Evans & Sutherland Computer Corporation
600 Komas Drive
P.O. Box 58700
Salt Lake City, UT 84158
Point of contact: Jim Bleak
Phone: 801-588-1000 Fax: 801-588-4531

Specifications
Polygon capacity: Up to 4 million polygons per second, but usually around 500K.
Update rate: Operates at 60 Hz.
Transportation delay: Calculated as 2.5 image generator fields plus one display refresh field.
Anti-Aliasing: Uses a proprietary sub-pixel anti-aliasing technique.

Applications
One application is in high-fidelity military flight simulation, particularly in fast, fixed-wing aircraft. Large-area photoderived databases, including geospecific and geotypical gaming areas that exploit the possibilities of the global texture option, can be tailored for air-to-air, air-to-ground, and other training scenarios. High terrain fidelity and density for nap-of-the-earth flight, night, dawn or dusk, and day simulation, fast-jet collision detection, and MIP texture for height and distance cues also make the ESIG-4500 ideal for rotary-wing aircraft training. Other applications are in ground warfare, civilian aviation, driving, and maritime.

Maturity Level
This IG has already been developed.

9.2.5 G2000/ETX

Cost: $86,000

Vendor Information
AAI Corporation
P.O. Box 238
Hunt Valley, Maryland 21030-0238
Phone: 919-361-3800
Fax: 919-361-3888

Specifications
Polygon capacity: 120,000 polygons per second.
Update rate: Operates at 60 Hz.
Transportation delay: 53 msec at 60 Hz, which equals 3+ frames.
Anti-Aliasing: Uses 4X4 subpixel anti-aliasing.

Applications
The G2000/ETX is used in various virtual environment applications.

Maturity Level
This IG has already been developed.

9.2.6 VITAL VIII

Cost: Not Specified

Vendor Information
FlightSafety International
Visual Simulation Systems
5695 Campus Parkway
St. Louis, MO 63042-2338
Point of contact: Dan Myers
Phone: 314-551-8500
Fax: 314-551-8444

Specifications
Polygon capacity: 400,000 polygons per second.
Update rate: Operates at 50 Hz.
Transportation delay: 50 msec at 50 Hz, which equals 2.5 frames.
Anti-Aliasing: Uses 4X4 subpixel anti-aliasing.

Applications

Maturity Level
This IG has already been developed.

9.2.7 R3D/100 (PC accelerator, two chip)

Cost: Not Specified

Vendor Information:
Real 3D (a Lockheed Martin Company)
12506 Lake Underhill Road
Orlando, FL 32825-5002
Point of contact: John Lenyo
Phone: 407-826-3360
Fax: 407-826-3358

Specifications
Polygon capacity: Up to 750,000 three-edge polygons can be processed per second.
Update rate: Operates at 72 Hz.
Transportation delay: One additional field/frame time.
Anti-Aliasing: Support for multi-pass anti-aliasing is provided.

Applications

Maturity Level
These IG chips have already been developed.

9.3 Visual Databases

Visual databases serve to create the graphics that are shown on the displays for virtual environment systems. They are interactive, and allow the user to create, edit, and view 3-D, fully textured scenes and instrumentation. Many contain object libraries, in which a standard part or object can be pulled form the database and displayed on the screen.

Important performance categories for visual databases are:
Model Switching (Limited detail switching) - Need more detail on objects that are close to the user's viewpoint.
Object libraries - Objects can be made and saved in the object libraries, or they can be purchased from companies that specialize in making different objects.

Current state of this technology: Visual databases currently meet the needs of the VE community, the only limitation is in the image generator.

9.3.1 MultiGen

Cost: $100,000

Vendor Information
MultiGen Inc.
550 S. Winchester Blvd., #500
San Jose, CA 95128
Point of contact: Juli Godsil
Phone: 408-261-4100
Fax: 408-261-4101

Platforms supported
SGI

Applications
MultiGen is the premier choice of professional modelers in flight, ground and marine simulation, accident reenactment, virtual reality, entertainment, and other real-time applications.

Maturity Level
This visual database is fully developed.

9.3.2 dVise

Cost: $55,000 - $200,000

Vendor Information
Division Incorporated
39555 Orchard Hill Place, Suite 205
Novi, MI 48375
Point of contact: Will Siembor
Phone: 810-348-1683
Fax: 810-348-1751

Platforms supported
SGI

Applications
MultiGen is the premier choice of professional modelers in flight, ground and marine simulation, accident reenactment, virtual reality, entertainment, and other real-time applications.

Maturity Level
This visual database is fully developed.

9.3.3 VRCreator Pro

Cost: $495

Vendor Information
VREAM
2568 North Clark Street
Suite 250
Chicago, IL 60614
Phone: 312-477-0425
Fax: 312-477-9702

Platforms supported
DOS

Applications
VRCreator Pro is targeted for professional VRML content developers.

Maturity Level
This visual database is fully developed.

9.3.4 WorldToolKit

Cost: $795 - $12,000

Vendor Information
SENSE8 Corporation (Headquarters)
100 Shoreline Highway, Suite 282
Mill Valley, CA 94941
Phone: 415-331-6318
Fax: 415-331-9148

Platforms supported
DOS
SGI
Windows
Sun
NT

Applications
WorldToolKit Release 6 incorporates the philosophy of OpenVRTM. This means that WorldToolKit R6 is portable across platforms, including SGI, Sun, HP, DEC, Intel, PowerPC, and Evans and Sutherland. WorldToolKit R6 is optimized to make full use of the unique capabilities of each platform to deliver the fastest graphics possible. A set of optimization functions unique to each platform interfaces directly with each system's graphics libraries. In addition, WorldToolKit R6 supports a wide variety of input and output devices, and also allows you to incorporate existing C code-such as device drivers, file readers, and drawing routines-and to interface with a variety of information sources.

Maturity Level
This visual database is fully developed.

9.3.5 Superscape VRT

Cost: $5,000

Vendor Information
Superscape, Inc.
2483 E. Bayshore Rd.
Suite 103
Palo Alto, CA 94303
Phone: 415-812-9380
Fax: 415-812-9390

Platforms supported
DOS

Applications
With VRT, Release 4, Virtual Worlds and complete VR applications can be built both quickly and easily. VRT provides single click instant access to every module of VRT's integrated authoring suite. The user extendible library of Virtual Clip Art provides ready-made objects for rapid inclusion in Virtual Worlds. Superscape Virtual Clip Art objects come complete with textures, sounds, dynamics and unique behaviors.

Maturity Level
This visual database is fully developed.

9.4 Head Mounted Displays

Head Mounted Displays (HMDs) project the images of the virtual environments directly in front of the eyes. HMDs can display 3-D images with the use of stereo graphic viewing. There are a variety of display types that include CRTs, LCDs, and Fiberoptics.

Important performance characteristics for HMDs are:
Field of View - how much of a scene can be observed in the HMD at one time. (A horizontal field of view of 80 to 100 degrees is often cited as the threshold of immersion.)
Resolution - the clarity of the picture seen in the HMD.
Lag - the lag time associated with the HMD. The lag should be 75 milliseconds or less.
Update rate - the number of pictures ran per interval of time. The update rate should be targeted at around 60 Hertz.
Weight - the actual weight of the HMD.

Current state of this technology: HMDs are limited by the trade-off between field of view and resolution. The trend is for narrower fields-of-view with correspondingly higher resolution. Technology for really decent HMDs is still about 3-4 years away from being developed. It is also believed that HMDs contribute to simulator sickness, so this is an issue that also needs to be addressed in the future.

9.4.1 dVisor

Cost: $6,900

Vendor Information:
Division Incorporated
The Courtyard, #10
431 West Franklin Street
Chapel Hill, NC 27516
Point of contact: Will Siembor
Phone: 810-348-1683
Fax: 810-348-1751

Specifications
Type: Color LCD
Field of view: 105(H) X 41(V)
Resolution: 345 X 259
Weight: 80 oz.

Maturity Level
This HMD is already available.

9.4.2 CyberEye ACE-200N

Cost: $2,595

Vendor Information:
General Reality Company
124 Race Street
San Jose, CA 95126
Point of contact: Denny Reiner
Phone: 408-289-8340
Fax: 408-289-8258

Specifications
Type: Dual Active Matrix LCD
Field of view: 35(H) X 26(V)
Resolution: 789 X 230
Weight: 16 oz.

Maturity Level
This HMD is already available.

9.4.3 CyberEye CE-200N

Cost: $1,895

Vendor Information:
General Reality Company
124 Race Street
San Jose, CA 95126
Point of contact: Denny Reiner
Phone: 408-289-8340
Fax: 408-289-8258

Specifications
Type: Dual Active Matrix LCD
Field of view: 22.5(H) X 16.8(V)
Resolution: 789 X 230
Weight: 14 oz.

Maturity Level
This HMD is already available.

9.4.4 ClearVue

Cost: $100,000

Vendor Information:
Hughes Training, Inc.
Link Division
P.O. Box 1237
Binghamton, NY 13902-1237
Point of contact: Werner Kraemer
Phone: 607-721-4356
Fax: 607-721-5600

Specifications
Type: Monochrome CRT with LC Filters
Field of view: 80(H) X 40(V)
Resolution: 1280 X 1024
Weight: 3 lb. 5 oz.

Maturity Level
This HMD is already available.

9.4.5 VFX 1 HEADGEAR

Cost: $995

Vendor Information:
FORTE Technologies, Inc.
1057 E. Henrietta Rd.
Rochester, NY 14623
Point of contact: Peter Matthews
Phone: 716-427-8595
Fax: 716-292-6353

Specifications
Type: Active Matrix Color LCD
Field of view: 33.45(H) X 25.46(V)
Resolution: 789 X 230
Weight: 32 oz.

Maturity Level
This HMD is already available.

9.4.6 1000HRpv VIM

Cost: $7,995

Vendor Information:
Kaiser Electro-Optics, Inc.
2752 Loker Ave. West
Carlsbad, CA 92008
Point of contact: Charles Bragdon
Phone: 619-438-9255
Fax: 619-438-6875

Specifications
Type: LCD
Field of view: 100(H) X 30(V)
Resolution: 800 X 225
Weight: 26 oz.

Maturity Level
This HMD is already available.

9.4.7 Full Immersion HMD

Cost: $50,000

Vendor Information:
Kaiser Electro-Optics, Inc.
2752 Loker Ave. West
Carlsbad, CA 92008
Point of contact: Frank Hepburn
Phone: 619-438-9255
Fax: 619-438-6875

Specifications
Type: Active Matrix LCD
Field of view: 150(H) X 50(V)
Resolution: 1280 X 1024
Weight: 2 lb.

Maturity Level
This HMD is already available.

9.4.8 CYBERFACE 2

Cost: $8,100

Vendor Information:
LEEP Systems, Inc.
241 Crescent St.
Waltham, MA 02154
Point of contact: Craig Schiller
Phone: 617-647-1395
Fax: 617-647-7709

Specifications
Type: 2 Active Matrix Color LCDs
Field of view: 140(H) X 110(V)
Resolution: 385 X 119
Weight: 32 oz.

Maturity Level
This HMD is already available.

9.4.9 CYBERFACE 5

Cost: $45,000

Vendor Information:
LEEP Systems, Inc.
241 Crescent St.
Waltham, MA 02154
Point of contact: Craig Schiller
Phone: 617-647-1395
Fax: 617-647-7709
Specifications
Type: 4 Active Matrix Color LCDs
Field of view: 140(H) X 60(V)
Resolution: Triple resolution
Weight: 26 oz.

Maturity Level
This HMD is already available.

9.4.10 MRG4

Cost: $2,199

Vendor Information:
Liquid Image Corp.
659 Century St.
Winnipeg MB R3H, Canada
Point of contact: Daryl Makinson
Phone: 204-772-0137
Fax: 204-772-0239

Specifications
Type: 4 Active Matrix Color LCDs
Field of view: 61(H) X 46(V)
Resolution: 479 X 234
Weight: 2.2 lb.

Maturity Level
This HMD is already available.

9.4.11 Full Color Datavisor HighRes

Cost: $44,900
Note: Add $5,000 for see-through mode option.

Vendor Information:
n-Vision, Inc.
Suite 1B-10
7915 Jones Branch Dr.
McLean, VA 22102
Phone: 703-506-8808 (3033)
Fax: 703-903-0455

Specifications
Type: CRT's
Field of view: 87.5(H) X 50(V)
Resolution: 1280 X 1024
Weight: 3.5 lb.

Maturity Level
This HMD is already available.

9.4.12 i-glasses! (VGA)

Cost: $3,500

Vendor Information:
Virtual i-O, Inc.
Suite 600
1000 Lenora St.
Phone: 206-382-7410
Seattle, Washington 98121
Fax: 206-382-8810

Specifications
Type: Active Matrix LCD's
Field of view: 22.25(H) X 19(V)
Resolution: 640 X 480
Weight: 8.5 oz.

Maturity Level
This HMD is already available.

9.4.13 High-Res. Color HMD 133

Cost: $40,000

Vendor Information:
Virtual Reality, Inc.
485 Washington Ave.
Phone: 914-769-0900
Pleasantville, NY 10570
Fax: 914-769-7106

Specifications
Type: Field Sequential CRTs
Field of view: 40(H) X 30(V)
Resolution: 1280 X 960
Weight: 3 lb.

Maturity Level
This HMD is already available.

9.4.14 VR 5

Cost: $40,000

Vendor Information:
POC: Evan
Phone: 914-769-0900
Fax: 914-769-7106

Specifications
Type: Field Sequential CRTs
Field of view: 40(H) X 30(V)
Resolution: 1280 X 960
Weight: 3 lb.

Maturity Level
This HMD is already available.

9.5 Virtual Retinal Displays

Developer Information
Human Interface Technology Lab
The University of Washington
215 Fluke Hall
Box 352142
Seattle, WA 98195-2142
Point of contact: Arthur Kerr
Phone: 206-616-1477 Fax: 206-543-5380

Maturity Level
The Virtual Retinal Display (VRD) team has been focused on developing improvements to the current prototype systems and on creating the parts needed for future prototypes. The VRD, based on the concept of scanning an image directly on the retina of the viewer's eye, is being developed under a four-year program funded by Microvision, Inc. The program began in November 1993 with the goal of producing a full color, wide field of view, high resolution, high brightness, low cost stereo display in a package the size of conventional eyeglasses.

Two prototype systems are currently being demonstrated. The first is a bench mounted unit that will display a full color, VGA (640 by 480) resolution image updated at 60 Hertz. It will operate in either an inclusive or see-through mode. The second is a portable unit that will display a monochrome, VGA resolution image. The portable system is housed in a briefcase allowing for system demonstrations at remote locations.

Techniques that expand the system's exit pupil, making it easier to align one's eye to the display, have been developed and demonstrated for a monochrome display. Work is continuing to optimize the design and to develop components that will expand the pupil of the color system.

The largest component in the portable system is the commercially purchased vertical (60 Hertz) scanner. A new vertical scanner is being designed that should significantly decrease devices size and cost. Once this design is complete a head-mounted demonstration prototype will be assembled.

9.6 Body Trackers

Body trackers are used to track the motion of the user so that tasks can be performed in the virtual environment. There are a variety of tracker types, and they are electromagnetic, optical, mechanical, acoustical, and combination. There are advantages and disadvantages to each tracker.

- Important performance characteristics for body trackers are:
- Tracking multiple points - is the tracker capable of tracking more than one point.
- Accuracy and Range - the distance and accuracy of the trackers.
- Immunity to interference - what causes interference with the tracker used.
- Lag - what kind of time delay is involved in using a tracker.

Current state of this technology: Trackers currently have limitations depending on which technology is being used. For example, magnetic trackers are adversely affected by metallic objects in the area. Other trackers have limitations of a similar nature.

9.6.1 Flock of Birds

Cost: $8,090

Vendor Information
Ascension
P.O. Box 527
Burlington, VT 05402
Point of contact: Jack Scully
Phone: 802-860-6440 (ext.11)

Specifications
Type of tracker: Magnetic
Number of points tracked: 30
Frequency: 144 Hz
Range: 10 ft

Maturity Level
This body tracker is already available.

9.6.2 FasTrak

Cost: $6,050

Vendor Information
Polhemus
One Hercules Drive
P.O. Box 560
Colchester, VT 05446

Specifications
Type of tracker: Magnetic
Number of points tracked: 4
Frequency: 120 Hz
Range: 10 ft

Maturity Level
This body tracker is already available.

9.6.3 IsoTrak II

Cost: $2,675

Vendor Information
Polhemus
One Hercules Drive
P.O. Box 560
Colchester, VT 05446

Specifications
Type of tracker: Magnetic
Number of points tracked: 2
Frequency: 120 Hz
Range: 5 ft

Maturity Level
This body tracker is already available.

9.6.4 VR360

Cost: $9,200

Vendor Information
Angularis

Specifications
Type of tracker: Inertial
Number of points tracked: 1
Frequency: 500 Hz
Range: 20 ft

Maturity Level
This body tracker is already available.

9.6.5 Vscope

Cost: $2,800

Vendor Information
Lipman

Specifications
Type of tracker: Ultrasonic
Number of points tracked: 1
Frequency: 100 Hz
Range: 12 ft

Maturity Level
This body tracker is already available.

9.7 Hand Trackers (Gloves)

Data gloves are used to track the motion of the hand and fingers so that tasks can be performed in the virtual environment.

- Important performance characteristics for hand trackers are:
- Number of sensors - the more sensors used generally results in a more realistic glove.
- Sensor Resolution - the smallest degree amount that the sensor will recognize. This should remain constant over the entire range of joint motion.
- Repeatability Between Glove Wearings - The standard deviation in degrees.
- Update Rate - frequency of position updates.

Current state of this technology: One problem with the glove is the need to provide a sense of touch to increase the haptic experience to the wearer. Work is under way to achieve this illusion by making the glove resist further closure, but these gloves are not without their difficulties because they can be tiring and feel artificial.

9.7.1 5th glove

Cost: $500

Vendor Information:
General Reality
124 Race St.
San Jose, CA 95126
Point of contact:
Phone: 408-289-8340
Fax: 408-289-8258

Specifications
Type: Fiberoptic
Number of sensors: 5
Sensor resolution: 8-bits (256 positions per finger)
Repeatability Between Glove Wearings:
Update Rate: 200 Hz

Applications
The new 5th Glove features advanced fiber-optic flex sensors to generate finger-bend data. Move easily through your virtual world by combining hand gestures with the pitch and roll of your hand.

Maturity Level
This hand tracker is already available.

9.7.2 CyberGlove (18)

Cost: $9,800

Vendor Information:
Virtual Technologies
2175 Park Boulevard
Palo Alto, California 94306
Point of contact:
Phone: 415-321-4900
Fax: 415-321-4912

Specifications
Type: Resistive bend sensing
Number of sensors: 18
Sensor resolution: 0.5 degrees
Repeatability Between Glove Wearings: 1 degree
Update Rate: 112 records per second

Applications
Virtual reality, telerobotics, task training, medicine, CAD, sign language recognition, video games, graphical character animation, music generation, hand-function analysis, and many others.
The CyberGlove is a low-profile, lightweight glove with flexible sensors which accurately and repeatably measure the position and movement of the fingers and wrist. The award-winning design uses the latest in high-precision joint-sensing technology and is state-of-the-art in instrumented gloves.

Maturity Level
This hand tracker is already available.

9.7.3 CyberGlove (22)

Cost: $14,500

Vendor Information:
Virtual Technologies
2175 Park Boulevard
Palo Alto, California 94306
Point of contact:
Phone: 415-321-4900
Fax: 415-321-4912

Specifications
Type: Resistive bend sensing
Number of sensors: 22
Sensor resolution: 0.5 degrees
Repeatability Between Glove Wearings: 1 degree
Update Rate: 112 records per second

Applications
Virtual reality, telerobotics, task training, medicine, CAD, sign language recognition, video games, graphical character animation, music generation, hand-function analysis, and many others.

The CyberGlove is a low-profile, lightweight glove with flexible sensors which accurately and repeatably measure the position and movement of the fingers and wrist. The award-winning design uses the latest in high-precision joint-sensing technology and is state-of-the-art in instrumented gloves. The 22-sensor model adds sensors to measure the flexion of the distal joints on the four fingers.

Maturity Level
This hand tracker is already available.

9.8 Sound Systems

Sound systems need to have the capability to generate sound in 3-D, which means sound can come from the left, the right, up, down, the front, the back or any combination. Additionally, environmental effects such as Doppler, and sound reflections off surfaces should be possible to reproduce using the sound system.

Important performance characteristics for 3-D sound systems are:
Number of input channels - More inputs generally equate to more realistic 3D sound.
Type of System - Could be a PC board, a stand alone system, etc.

Current state of this technology: At present, sound systems are relatively crude, but much research is underway to create convincing and realistic three dimensional sounds at exactly the right moment and from the right direction. (For example, making a proper sound when a glove hits a wall.)

9.8.1 Acoustetron II

Cost: $12,000

Vendor Information
Crystal River Engineering
490 California Ave
Suite 200
Palo Alto, CA 94306
POC: Jack Scully
Phone: 415-323-8155
Fax: 415-323-8157

Specifications
Input Channels: 8
Type: Stand alone system

Applications
The Acoustetron II adds high-end 3D audio rendering to 3D graphics workstations, for use in real-time rendered 3D environments, such as VR rides, training simulators, and virtual prototyping systems.

Maturity Level
This sound system is already available.

9.8.2 Audio Architect

Cost: $500

Vendor Information
Corporate Communications
VSI Visual Synthesis Incorporated
4126 Addison Rd.
Fairfax, VA 22030
Phone: 703-352-0258 Fax: 703-352-2726

Specifications
Input Channels: 2
Type: Development system for SGI, Sun, DEC

Applications
Audio Architect is designed for those developers that want primarily sonification capability. WorldToolKit, GVS, developers of financial applications, virtual environments prototypes, architectural walk-throughs, data support models, medical analysis, general research, entertainment applications, digital media and training materials use Audio Architect.

Maturity Level
This sound system is already available.

9.8.3 Sonic Architect

Cost: $1,500

Vendor Information
Corporate Communications
VSI Visual Synthesis Incorporated
4126 Addison Rd.
Fairfax, VA 22030
Phone: 703-352-0258 Fax: 703-352-2726

Specifications
Input Channels: 2
Type: Development system for SGI, Sun, DEC, absorption and reflection models.

Applications
Developers of virtual environments, real-time simulations, architectural walk- throughs, various driving simulators, medical research, entertainment applications, digital media and training materials use Audio Architect.

Maturity Level
This sound system is already available.

9.8.4 Audio Image SoundCube

Cost: $8,000

Vendor Information
Corporate Communications
VSI Visual Synthesis Incorporated
4126 Addison Rd.
Fairfax, VA 22030
Phone: 703-352-0258 Fax: 703-352-2726

Specifications
Input Channels: 8
Type: Stand alone system

Applications
Developers of virtual environments, real-time simulations, architectural walk- throughs, medical simulations, general research, entertainment applications and location based entertainment use SoundCube.

Maturity Level
This sound system is already available.

9.9 Force Feedback Systems

Force feedback systems use the sense touch, so that the user has the sense that the virtual object actually exists. (For example, a user touches a virtual wall, and the force feedback system doesn't allow them to go through the wall.)

Important performance characteristics for force feedback systems are:
Location of the force feedback - Area of the body where the force feedback is felt.
Degrees of freedom - In how many directions does the force feedback act.

Current state of this technology: Force feedback systems are currently in their infancy.

9.9.1 PHANToM

Cost: $19,000

Vendor Information
SensAble Technologies, Inc.
26 Landsdowne Street
University Park at MIT
Cambridge, MA 02139
Phone: 617-621-0150 Fax: 617-621-0135

Specifications
Location of the force feedback: One finger
Degrees of freedom: 6

Applications
It can be used for any "touchable" virtual objects of various size, shape, and texture. The constraint on the size the virtual object is 7.5X10.5X15 inches, however there is an optional workspace upgrade that will increase the standard PHANToM 300% while maintaining force and resolution specifications.

Maturity Level
This force feedback system is already available.

9.9.2 Teletact II

Cost: $4,900
Note: Teletact II control system is an additional $13,400

Vendor Information
ARRC/Airmuscle Ltd.
University Road
Salford, England M5 4PP
Phone: 4461-745-7384
Fax: 4461-745-8264

Specifications
Location of the tactile feedback: Fingers and hand.

Applications
Teletact offers force feedback and tactile feedback by using small airbags inside the lining of the TeleTact Glove. When worn, the user can feel the size, shape, and some texture of a virtual or remote object because the airbags quickly fill and deflate to provide touch sensations to the hand.

Maturity Level
This force feedback system is already available.

9.9.3 Exoskeletal Master (prototype)

Cost: $100,000

Vendor Information
Sarcos and the Center for Engineering Design
216 East 300 South, Suite 150
Salt Lake City, UT 84111
Phone: 801-531-0559
Fax: 801-531-0315

Specifications
Location of the tactile feedback: Hands and Arms

Applications
This was developed at the University of Utah and is the leading system of its type in the world. High-pressure hydraulic lines precisely control the forces being applied to the operator's arms and hands.

Maturity Level
This force feedback system is only in it's prototype stage.

9.9.4 PER-Force Hand Controller

Cost: $15,500

Vendor Information
Force Feedback Devices
1919 Green Road
Ann Arbor, MI 48105
Phone: 313-668-2567

Fax: 313-668-8780

Specifications
Location of the tactile feedback: Hands
Degrees of freedom: 6

Applications
It is a hand feedback system that mounts to a desk or other flat surface. The operator may them grap a handle grip to use the system. It's main advantage over the ARM is its light weight and small size.

Maturity Level
This force feedback system is already available.

9.10 Tactile Systems

Tactile systems give the user the sense of actually touching a virtual object, however it doesn't necessarily give the user the sense that the object actually exists. (For example, a person touches a virtual wall and although they can feel when they reach the wall, nothing prevents them from extending their hand on through the wall.) Tactile systems also often provide temperature feedback to the user.

Important performance characteristics for tactile systems are:
Location of the force feedback - Area where force is felt.

Current state of this technology: Tactile systems are currently in their infancy.

9.10.1 CyberTouch (Works with the CyberGlove)

Cost: $14,800

Vendor Information
Virtual Technologies, Inc.
2175 Park Boulevard
Palo Alto, California 94306
Phone: 415-321-4900

Fax: 415-321-4912

Specifications
Location of the tactile feedback: Finger tips and the palms.
Note: This only works as an option to the CyberGlove.

Applications
CyberTouch allows anyone to use their hands to interact with objects in a virtual world. It lets you feel a virtual object and know it is in your hand without having to look.

Maturity Level
This tactile system is already available.

9.10.2 DTSS X/10

Cost: $10,000

Vendor Information
CM Research
Instrumentation for the Information Age
2437 Bay Area Blvd. No. 234
Houston, TX 77058
Phone: 713-488-3598
Fax: 713-488-3599

Specifications
Location of the tactile feedback: Skin.

Applications
The Displaced Temperature Sensing System (DTSS) provides haptic feedback, specifically touch and temperature. With the DTSS the user can feel the temperature of a remote location (Real or Unreal) as if they were there.

Maturity Level
This tactile system is already available.

9.10.3 Tactools XTTI

Cost: $1,500 - with one tactor

Vendor Information
Xtensory Inc.
140 Sunridge Dr.
Scotts Valley, CA 95066
Phone: 408-439-0600
Fax: 408-439-9709

Specifications
Location of the tactile feedback: Fingers and hand.

Applications
Uses a controller that can support up to 10 tactors. Communicates over serial or MIDI ports. A tactor is a small transducer that can create minute vibrations or momentary impulses and can be placed anywhere on the skin.

Maturity Level
This tactile system is already available.

9.10.4 TouchMaster

Cost: $8,500

Vendor Information
EXOS Inc.
8 Blanchard Rd.

Burlington, MA 01803
Phone: 617-270-2075 Fax: 617-270-5901

Specifications
Location of the tactile feedback: Fingers.

Applications
A non-reactive, tactile feedback system specifically designed for use in virtual environments for experimentation.

Maturity Level
This tactile system is already available.

9.11 Human Models

Other human models that are currently available on the market are listed below.

9.11.1 The McDonnell Douglas Human Modeling System (MDHMS)

Cost: Not Specified

Vendor Information:
McDonnell Douglas, Long Beach Division
Point of contact: Mike Biferno
Phone: (310) 593-7094

Description
MDHMS enables electronic simulation/demonstration of assembly, operations and maintenance early in the design process using 3D animated human manikins. MDHMS is a menu-driven, interactive computer program used to define design requirements and aid in design evaluation.

Maturity Level
This human modeling system is already available.

9.11.2 SafeWork

Cost: Not Specified

Vendor Information:
GENICOM Consultants, Inc.
3400 De Maisonneuve West,
1 Place Alexis-Nihon,
Suite 1430
Montreal, Quebec, Canada, H3Z 3B8
Point of contact: Robert Carrier
Phone: 514-931-3000 Fax: 514-931-2118

Description

Safework is used to model humans physically, and simulate their interactions with the environnement for various applications. Safework is particulary intended for people who wish to improve comfort, health, safety, productivity at work and product quality.

Maturity Level
This human modeling system is already available.

9.11.3 ADAMS/Android

Cost: Not Specified

Vendor Information:
Mechanical Dynamics, Inc.
2301 Commonwealth Blvd.
Ann Arbor, MI 48105
Point of contact: Stacey Hamill
Phone: 313-913-2539 Fax: 313-994-6418

Description
The software enables the user to easily create dynamically realistic human models and then use ADAMS to study kinematic, static, and dynamic behavior involved in complex human-machine systems. Using a database of population characteristics, ADAMS/Android enables users to automatically build humanoids either by simply selecting a percentile man, woman, or child, or by specifying explicit height and weight values. Joints can be driven by time-dependent motion (kinematics or inverse dynamics) or by time-dependent or displacement-dependent forces (dynamics).

Maturity Level
This human modeling system is already available.

9.11.4 SIMM/Gait

Cost: Not Specified

Vendor Information:
MusculoGraphics, Inc.
1840 Oak Avenue
Evanston, IL 60201
Point of contact: Arthur Wong
Phone: 708-866-1882 Fax: 708-866-1808

Description
SIMM/Gait allows users to easily animate three-dimensional motion data for gait analysis applications. It also includes file translators to animate data files from commercial motion capture systems. Two key features: 1) SIMM/Gait animations display ground reaction force vectors superimposed on a skeleton, and 2) SIMM/Gait animations can also display changes in muscle EMG activation during gait by changing muscle color.

Maturity Level
This human modeling system is already available.

9.11.5 Deneb/ERGO

Cost: Not Specified

Vendor Information:
Deneb Robotics, Inc.
3285 Lapeer Road West
P.O. Box 214687
Auburn Hills, MI 48321
Phone: 810-377-6900
Fax: 810-377-8125

Description
Deneb/ERGO is an interactive, 3-D graphic simulation and ergonomic analysis tool for ergonomic assessment and task analysis. It provides an easy-to-use human motion programming interface for rapid prototyping of human motion within a work area.

Maturity Level
This human modeling system is already available.

9.11.6 The Observer

Cost: Not Specified

Vendor Information:
Noldus Information Technology Inc.
6 Pidgeon Hill Drive, Suite 180
Sterling, VA 20165
Phone: 703-404-5506
Fax: 703-404-5507

Description
The Observer is a professional software system for observing, coding and analyzing series of events. You can use it to record activities, postures, movements, positions, facial expressions, social interactions or any other aspect of human behavior.
Ergonomics: usability testing of man-machine interfaces, software prototypes or consumer products, and working posture analysis.
Human factors studies: workflow analysis, labor and time studies, and efficiency research.

Maturity Level
This human modeling system is already available.

10. APPENDIX B: TECHNOLOGY DEVELOPERS

H	S	A		F	T	I	Location	Description	Point of Contact	Further Information
X	X			X	X		AL / CFB (USAF)	Human Sensory Feedback	Capt Debra A. North Program Manager	http://www.al.wpafb.af.mil/cfb/hsf.htm
	X				X	X	ARI (Army)	Integrated virtual environment research and development.	Dr. Goldberg, DSN: 960-4690/ (407)380-4690	http//205.130.63.3/ ssru.htm
					X	X	Ascension	One of the lead providers of body position tracking devices	Jack Scully, (802)860-6440, Ext. 11	http://www.ascension-tech.com/
X			X	X	X	X	Boeing	Integrating technologies for maintenance support of commercial aircraft	Dr. William McNeely (206) 865 -3614	
		X					Brown Innovations	3-D Sound Dome	BiiVAI@PureStereo.Com (773) 296-6400	http://www.purestereo.com/brown.html
X					X	X	Computer Graphics Sys. Dev. Corp.	TOPIT™ simulator & OmniTrek™ treadmill	rlatham@cgsd.com (415) 903 - 4920 Roy Latham	http://www.cgsd.com/main.html
X	X	X	X	X	X	X	DARPA	DARPA has projects in probably all areas.	Various POCs	http://www.arpa.mil/
			X				Deneb Robotics, Inc.	Virtual Manufacturing and Simulation	marketing@deneb.com (810) 377-6900	http://www.deneb.com
	X		X		X		Division, Inc.	Currently well known for human figure model, also an integrator for VR	info@division.com (415) 312.8200	http://www.division.com
X							EXOS Inc.	Sensory Exoskeleton Arm-Master for Robot Control	Acquired by Microsoft Corp. in April 1996.	
	X				X	X	Fakespace	VR interaction devices, BOOM™ and Interactive Workbench	info@fakespace.com (415) 688-1940	http://www.fakespace.com/index.html
	X				X	X	General Reality Co.	VR input and HMD displays	sales@genreality.com (408) 289-8340	http://www.genreality.com/
						X	GYRATION, Inc.	3D Inertial Mouse	Laurie Schuler (408) 973-7078	http://www.gyration.com/desk.html
					X		Johnson Kinetics	New approach to position tracking	physiokine@aol.com (937) 427-3626	http://members.aol.com/physiokin/

H = Haptic (Force Feedback) S = See (Visual Displays) A = Auditory M = Human Figure Models
I = Input Devices F = Tactile Feel T = Tracking Devices and Lag

H	S	A		F	T	I	Location	Description	Point of Contact	Further Information
			X				McDonnell-Douglas	MDHMS (Teamed with Division, Inc.)	Mike Biferno (310) 593-7094	http://pat.mdc.com/LB/ LB.html
	X						MultiGen Inc.	Scene generation databasing	sales@multigen.com (408) 261-4100	http://www.multigen.com/
	X	X		X	X	X	NASA Ames	Very broad base of VR research	Cynthia Null, PhD (415) 604-3323	http://www.arc.nasa.gov/
			X	X			NASA Johnson	Issues for the space usage and training	R. Bowen Loftin, PhD (713) 483-8070	bowen@gothamcity.jsc. nasa.gov
	X				X	X	NPS (Monterey)	Primarily geared towards networking of resources for VR work.	Mike Zyda, PhD (408) 656-2305	http://www.cs.nps.navy.mil/ research/projects.html
					X	X	Polhemus	The other lead in body position tracking devices	sales@polhemus.com. (800) 357-4777	http://www.polhemus.com/
	X						Pyramid Systems, Inc.	SID visual systems	psi_sales@pyramidsystems.com (810) 356-2662	http://www2.pyramidsystems. com/psi/Home.html
X							SensAble Technologies	Makers of the PHANToM™ thimble haptic device	SensAble@sensable.com (617) 621-0150	http://www.sensable.com/
			X				Transom Tech. Inc.	Commercial provider of UPenn's *Jack™* HFM	info@transom.com (313) 761-6001	http://www.transominc. com/
	X					X	U of Illinois (Chicago)	Developer of the CAVE™	(312) 996-3002	http://www.evl.uic.edu/ EVL/VR/
X	X			X		X	U of NC (Chapel Hill)	Research in various VR areas	http://www.cs.unc.edu/ Research/	
			X				U of Pennsylvania	Creator of UPenn's *Jack™* HFM	badler@central.cis.upenn.edu (215) 898-5862	http://www.cis.upenn.edu/ ~hms/home.html
X	X			X		X	U of Washington	One of the premiere sites for human interface in VR	Thomas A. Furness III, Ph.D. (206) 543-5075	http://www.hitl.washington.e du
						X	Virtual Space Devices, Inc	Locomotion input devices	info@vsdevices.com (612) 884-2455	http://www.vsdevices.com/
				X		X	Virtual Technologies	Glove vibrotactile stimulators and hand position tracker/input	info@virtex.com (415) 321-4900	http://users.quake.net/ ~virtex/products.html

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